Summary Slides from the

NASA ESTO Lidar Investment Strategy Update Community Forum - February 24, 2016

Pages 2 - 71

and the

NASA ESTO Microwave Remote Sensing Investment Strategy Update Community Forum - March 17, 2016

Pages 72 – 133

Overview of NASA ESTO Lidar Investment Strategy Update

Community Forum

February 24, 2016

Purpose of the ESTO 2016 Lidar Strategy Update

- The last ESTO Lidar investment strategy is almost a decade old. State of the art has progressed and new areas have been entering the scene (e.g., SmallSat instruments)
- Update strategy by identifying and summarizing key technology requirements and performance parameters based on measurement themes:
  - Atmospheric composition
  - Carbon & Ecosystems
  - Climate Variability & Change
  - Earth Surface & Interior
  - Water & Energy Cycle
  - Weather
- Opportunity for community to give input and play a role in shaping ESTO's future investment strategy

How will the final report be used?

- Use the input for upcoming ESTO AOs to inform ESTO's investment strategy
- Inform the Decadal Survey on the status of technology maturity
- Seek partnership opportunities with other agencies, industry, academia
- Identify emerging new technology trends and help infuse them into existing and future concepts

Lidar Technology Community Forum

- Transmitters State-of-the-Art and Future Requirements
- Receivers State-of-the-Art and Future Requirements
- Data Utilization and Acquisition Future Requirements
- Emerging Technologies and Trends

- **Transmitters State-of-the-Art and Future Requirements**
- **Receivers State-of-the-Art and Future Requirements**
- **Data Utilization and Acquisition Future Requirements**
- **Emerging Technologies and Trends**

Unmet Transmitter Technology Needs from 2007 Decadal Survey

Capability Gap	Measurements	TRL (Respondents)	"Greatest Challenge" TRL
Maturity and readiness of tunable lasers meeting measurement requirements	CO_2 (ASCENDS)	3-4	Power amplifier
Readiness	Aerosol/Clouds/Ecosystems (ACE)	4-5	Space qualification
Similar to LIST	3D Biomass (NISAR/GEDI, formerly DESDynI)	4-5	Space qualification
Readiness of laser systems	Gravity (GRACE II)	2-3	U.S. laser supplier
Multiple aperture transmitter	Topography (LIST in 2007 Decadal)	4-5	Multiple aperture system
Reliable UV transmitters meeting measurement requirements; 2 μm technology readiness and reliability	3D Winds	3-4	Laser readiness, reliability

Technology Needs for New Measurement Concepts

Capability Gap	Measurement	TRL (Respondents)	"Greatest Challenge" TRL
Blue-green laser technology readiness	Phytoplankton	3	2: Robust and reliable laser and frequency conversion system
Blue-green laser technology readiness	Ocean Mixed Layer	2	Robust and reliable laser and frequency conversion system
Tunable laser transmitter for CH_4 IPDA	Non-CO_2 Greenhouse Gases	4-5	3-4: Er:YAG and seed sources
Robust UV laser transmitter	Ozone	2, 4	2: Robust and reliable UV generation 290-320 nm
Multi-λ NIR laser transmitter readiness	Water vapor profiles	2 (LaRC); 5 (GSFC)	2: Robust and reliable 720 nm, 820 nm sources

Red/bold numbers in right column Represent reviewer revision of TRL

Technology Areas 2016

Technical Area	2006 Report	2016 Report	Rationale
1) mJ-class 1 μm lasers	X	**X**	Cross-cutting technology to several measurements
2) J-class 1 μm lasers	X	**X**	Cross-cutting technology to several measurements
3) 1-100 W 1.5-1.6+ μm lasers	X	**X**	Cross-cutting technology to several measurements
4) 1-20 W 2 μm lasers	X	**X**	Cross-cutting technology to several measurements
5) Seed and amplifier laser diodes		**X**	Cross-cutting component in laser technologies of many measurements
6) Parametric wavelength generation		**X**	Integrated with source laser, critical to specific measurements (*e.g.*, O_3, H_2O_v), *etc.*)
Harmonic wavelength conversions to UV-VIS/NIR	X	Drop, list with lasers 1) – 4)	Inextricably integrated with source laser
Other lasers	X	Drop, list with lasers 1) – 4)	Typically correlated parametric wavelength conversion

Specific Observations: Transmitters

- Laser component technology has evolved significantly
  - *Available wavelengths and WPE of pump and signal/seed laser diodes have changed significantly*
  - *Some new laser and nonlinear optical materials have emerged*
  - *Integration of photonic components into (much) smaller form factors with increased functional capabilities*
- Fiber laser *average* power capability now rivals traditional bulk solid-state systems
  - *"All" fiber architecture*: *compact and immune to misalignment*
    - Fused fiber pump combiners, fiber-integrated filters, fused fiber diagnostic taps
  - *Power scaling in "large mode area fiber"*
  - *Peak power limited by fiber core area; finite prospects for peak power scaling*
- Laser system architecture is evolving to take advantage of new capabilities
  - *Hybrid fiber/bulk solid-state systems*
    - Utilize best attributes of each technology: SWaP and misalignment immunity of fiber; peak power and energy scaling of bulk solid-state
    - *The* path to energy and peak power scaling of fiber lasers, and to waveform agility of bulk solid-state systems

Specific Observations: Transmitters

- General trends in laser component technology (*e.g.,* fibers, pump diodes, subsystem integration):
  - *Supplier issues*:
    - Foreign/domestic technology origin, manufacturing
      - ITAR/EAR
      - U.S. interests not necessarily a priority for foreign vendors
  - *Pump diode efficiency can be ≥ 60% at wavelengths < 1 μm*
    - ≤ 40% for "in-band" pumping of Er, much less at longer λ's ("in-band" for Tm)
  - *Fiber technology has improved dramatically, especially in average power scaling*
    - Yb, Er, Tm provide tunable laser output at 1-1.1, 1.5-1.6, and 1.8-2+ μm
    - "Telecom" type signal laser diodes enable large variation in temporal waveform (pulse rate/format)
    - Wide range of pulse durations are supported, including picosecond/femtosecond and "frequency comb" operation
    - Management of non-linearities is critical
- Transmitter (transceiver) pulse rate:
  - *If measurements can support pulse rates ≥ 10 kHz, fiber lasers may be enabling*
  - *For pulse rates ≤ 5 kHz fiber laser suitability will depend on specifics of laser operation, may still be valuable*

Specific Observations: Transmitters

- Synergistic DoD Contractor development
  - *National security programs in several measurement areas have focused on performance, SWaP advancements and space qualification*
  - *Average power, peak power, waveform/wavelength agility at 1, 1.5, 2, and 2-4 μm*
    - Waveform agility is a priority for a range of national security lidar applications, and development of waveform generation infrastructure is progressing to relatively advanced stage via contractor effort *under both internal and gov't funding*
      - *Includes FM/IM. scripted PRF variation and burst formats*
    - Significant advances have been made in high energy laser sources at 1 and 2 μm wavelengths
      - *Pulse energy up to ~ 1 J at PRF to ~ 5 kHz*
      - *Pulse energy to ≥ 10 mJ at PRF to 10's of kHz*
      - *cw "single aperture" MOPAs 10 ~ 20 kW* (@ 1 μm)
      - *Beam-combining* (*aperture summing, both coherent and incoherent*)
- Cross-cutting trends:
  - *Integrated Photonic Subsystems* (T_x, R_x, signal processing and mgmt., see full report)
    - Both monolithic and heterogeneous chip-scale integration promise dramatic improvements in performance, capability, and SWaP:
      - *Compact and EMI resistant transmitters/receivers, modulators and waveform generation, optical signal processing/ routing, optical to electronic transduction*
    - SWaP improvements are critical enablers for small-sat missions (esp. pico-sats)
  - *New pump diodes and fiber-MOPAs enable significant improvement in WPE*
  - *Hybrid fiber/bulk solid-state systems enable high power with waveform agility, SWaP*

Challenges

- Supplier issues
  - *U.S. investment strategy/vehicle for domestic technology companies and/or universities, e.g., SBIR, ACT, may not be adequate and needs higher level attention.*
- Emerging laser technologies
  - *Nonlinear optical materials for wavelength conversion*
    - Materials with improved nonlinear properties and/or phase-matching properties are needed. These are continuously evolving in several wavelength ranges via academic and industrial R&D
  - *Coatings*
    - Improved durability and damage resistant reflective and anti-reflective coatings are needed for laser optics, filter applications.
  - *Fiber lasers*
    - Interface components matched to emerging fibers are evolving continuously, are difficult to obtain.
      - *Filters, isolators, pump-combiners must be in form suitable for a continuous waveguide structure*
    - Nonlinear optical properties are often a critical impediment to end performance requirements
      - *The driving force for new fiber designs and material compositions* (*e.g*., non-silicate glasses)
    - New glass compositions are needed that enable wider range of laser ion doping and linear/nonlinear optical property control: explicitly *Materials Science* R&D <u>with potentially long gestation period</u>
  - *Hybrid Fiber/Bulk Solid-state Architectures*
    - Using fiber-MOPAs as the seed source with high-power bulk solid-state amplifiers may uniquely enable lidar measurements that simultaneously require high pulse energy and high average power
      - *The development of "hybrid" laser systems requires expertise in both technologies that may not be available in well-established technology development laboratories*
      - *Inter-organizational collaborations may be critical to establishing these development programs*

Challenges

- Slower than expected technology maturation
  - *Achieving SWaP goals*
    - An asymptotic process often characterized by incremental improvements
  - *Achieving reliability goals*
    - An asymptotic process often characterized by incremental improvements
  - *New technology insertion*
    - **Are there situations where abandoning a long development path is appropriate?**

2007 Decadal Survey Needs: 1 μm Solid-State Laser Transmitters

Measure-ment(s)	Technology	State of the Art	Requirements	Development Need
Topography, aerosol and T profiles	Pulse Rate ≤ 500 Hz, Solid-state Laser	λ ≈1 micron, ≥ 0.25 J @ 150 Hz PRF, WPE ~ 10%, 1 MHz linewidth, $M^2 < 1.5$[1]	λ ≈1 micron, 0.5 J @ 50 Hz PRF, WPE 6%, 1 MHz linewidth, $M^2 < 1.5$	Reliability, packaging, space qualification
Topography, aerosol and T profiles	Pulse Rate ≥ 1 kHz, Solid-state Laser	λ ≈1 micron: 1) **bulk,** ≥ 0.8 J @ 5 kHz PRF, WPE ~ 6%[2]; 2) **fiber,** > 1-4 mJ @ 10 kHz, WPE > 15%, GHz linewidth, $M^2 < 1.5$[3]	λ ≈1 micron, ~ 100's μJ @ ≥ 2.5 kHz PRF, WPE 6%, 1-MHz linewidth, $M^2 < 1.5$	Reliability, packaging, space qualification
Gravity	*cw* Solid-state Single Frequency Laser	λ ≈1 micron, ~ 15 kW, WPE ~ 10%, ~100 kHz linewidth, $M^2 < 1.5$[4]	1 micron, ≥ 20 mW, sub-Hz linewidth[5] (?)	Grace FO focused on frequency reference. MO (incl. λ) and details of locking scheme still in flux.
Atmospheric Composition, DWL, ocean mixing-layer	Frequency Conversion	see "Fixed Wavelength Conversion" and "Tunable Wavelength Conversion" charts	Harmonic generation of 532, 355 nm; parametric generation to fixed and **tunable λ's VIS-MWIR**	Improved nonlinear optical materials and anti-reflective coatings
Topography, aerosol and T, oceanography	**Fiber/Hybrid (bulk +fiber)**	10-100+ W at 1 μm (typically < 1 mJ), PRF 20-100+ kHz, M^2 ~ 1, WPE ≥ 20%	1, 1.5, 2 μm, ~ 0.1-few mJ @ ≥ 2.5 kHz PRF, WPE ≥ 15%, range of linewidths, $M^2 < 1.5$	Fiber-integrated components, low-nonlinearity gain fiber, higher WPE pump diodes
High resolution aerosol, $H_2O_{(v)}$, oceanography	Single λ signal laser diodes, amplifiers	10 kHz-few MHz linewidth, 20-100 mW P_{ave}	linewidth from kHz to MHz at variety of λ in VIS-SWIR range	Linewidth in ~ 10 kHz range, wavelengths > telecom

Red font indicates "Emerging Technology"

2007 Decadal Survey Needs: 1.5, 2 μm Solid-State Laser Transmitters

Measure-ment(s)	Technology	State of the Art	Requirements	Development Need
CO_2, Coherent DWL (aerosol)	Pulsed 2 μm, 1.57 μm laser	<u>CO_2</u>: ≥ 30% conversion to 1530-1625 nm via DFG w/ 1064 nm fiber-MOPA at high PRF. <u>DWL</u>: 2 μm Tm/Ho system under development at LaRC[6], > 1J @ ~ 200 ns.	CO_2: Pulsed 1.57 μm sources w/ P_{ave} ~ 5-20+ W, ~ 10 kHz PRF, ~ 1 μs pulsewidth, tunable. DWL: Pulsed 2 μm source @ 5-300 Hz @ E_{Pulse} ×SQRT(PRF) > 0.6 $JHz^{1/2}$, 8-GHz tunable frequency-agility, $M^2 < 1.2$, WPE > 5%.	<u>CO_2</u>: technology reliability and maturation, SWaP optimization. <u>DWL</u>: technology reliability and maturation, SWaP optimization.
CO_2	*cw* 1.57 and 2 μm laser	*Literature review in progress (see Final Report)*	3-5 W cw @ 2.05 microns, linewidth <50 kHz, 1-GHz tunable, λ stabilization to < MHz, FM/IM capability; 10% WPE. 10 W 1.57 μm tunable *cw* sources.	IM/FM waveform generation and control, technology maturation
CH_4	Pulsed ~1.65 μm laser	Few mJ, kHz Er:YAG, < 10% WPE, uses NPRO injection seed[7]	10 mJ/pulse, 1-3 kHz PRF, 10's of ns pulsewidth @ 1645 nm, tunable for DIAL	Q-switched oscillator, amplifier, WPE, SWaP
CO_2, CH_4	Fiber/Hybrid (bulk+fiber)	In active development, work to date focused on high PRF	~ 10 W P_{ave}, kHz PRF, ~ 1 μs pulsewidth <u>or</u> *cw*, tunable at selected λ	Integration of fiber-MOPA w/ bulk amplifiers; < 20 kHz PRF (Q-cw pumping of fiber amps) or *cw*
CO_2, CH_4	Single λ signal laser diodes	10 kHz-few MHz linewidth, < few mW P_{ave}	linewidth from kHz to MHz for DIAL tunable wavelength converters	Maturation of materials and designs for 1.6 – 2+ μm devices

Red font indicates "Emerging Technology"

2007 Decadal Survey Needs: Fixed Wavelength Conversion Transmitters

Measure-ment(s)	Technology	State of the Art	Requirements	Development Need
Aerosol, $H_2O_{(v)}$, T, oceanography (at 532 nm w/ less penetration than ~450-480 nm)	Second Harmonic Generation	~ 70% 1064nm → 532 nm (> 24 W @ 150 Hz, P_{pk} = 16 MW)[1]; > 50%, 1064nm → 532 nm (> 200 W)	> 100 mJ @ 532 nm, 10-200 Hz PRF; 2-5 mJ @ 532 nm, 2.5-20 kHz PRF	Incremental performance and reliability improvements
O_2	Second Harmonic Generation	> 50% 1530nm→765nm	1 J, 10 Hz.	Scale telecom technology lasers to much higher energy
DWL; aerosol and T profiles	Third Harmonic Generation	~ 6 W, ~ 50% 1064+532 → 355 nm (20 kHz, P_{pk} ~ 1 MW); ~ 20+% at 150-300 Hz PRF	~ 6 W, ~ 30% 1064+532 → 355 nm (200 Hz, P_{pk} ~ 10 MW	High efficiency, high reliability UV generation
None specified	Fourth Harmonic Generation	~ 20% 1064 → 532→266 nm (~ 10 W @ 20 kHz, P_{pk} = 0.25 MW)	< 10 Hz and > kHz systems 1-20 W range (in reference to O_3 meas)	High efficiency, high reliability UV generation

2007 Decadal Survey Needs: Tunable Wavelength Conversion Transmitters

Measure-ment(s)	Technology	State of the Art	Requirements	Development Need
$H_2O_{(v)}$, oceanography	OPO (vis-nir)	~ 17% conversion to ~ 450 nm via OPO+sum frequency w/ 1064 nm fundamental.[10] 532 nm pumped OPO/DFG for 700-1000 nm should be similar	**On/off resonance $H_2O_{(v)}$ NIR lines (720, 820, 940 nm); Optimized λ for ocean water transmission 400-480 nm**	High efficiency, high reliability VIS-NIR generation
GHG	OPO (SW/ MWIR)	≥ 30% conversion of 1 μm laser to 1530-1625 nm via DFG w/ 1064 nm fiber-MOPA at high PRF.[11]	Tunable source 1570-1650 nm for GHG DIAL, ~ 10 mJ @ kHz PRF	Average and peak power scaling, operation at PRF < 10 kHz, extension to λ > 1625 nm
O_3,	Cascaded Parametric (UV-VIS, NIR)	*Literature review in progress, similar to Fourth Harmonic Generation + sum frequency to reach 290-320 nm*	< 10 Hz and > kHz systems 1-20 W range to support **290-320 nm tunable systems**	High efficiency, high reliability UV generation
GHG	DFG/OPA (SW/MWIR)	> 10% DFG to 3-3.8 μm range demonstrated at high PRF using PPLN+1064 nm fiber MOPA	Tunable source 3-3.3 μm for CH_4 DIAL	Average and peak power scaling, operation at PRF < 10 kHz

Red font indicates "Emerging Technology"

Technology Needs Summary

	UV 355-400 nm	VIS 400-650 nm	NIR/SWIR 700-2000 nm	MWIR 3-5 micron
Measurement	3D Winds; Water vapor; Trop. ozone	Physical/biological oceanography; aerosols; topography	3D Winds; GHG; water vapor; O_2; topography; aerosols	GHG (CH_4)
Transmitter	**THG, OPO/OPA of 1-μm sources; multi-stage non-linear wavelength conversion**	**SHG of 1-μm sources; multi-stage non-linear wavelength conversion**	**1, 1.5, 1.8-2.6 μm sources; SHG of 1.5, 2 μm sources; OPO/OPA of 1 μm sources**	**OPO/OPA of 1, 1.5, 2 μm sources; narrow-gap laser diodes**
Detector	GaN, MCP, DD-CCD; Low-noise multi-element arrays, QE > 50% @ 355 nm	Si-APD, PMT; Gateable <50 ns, QE 50-70% @ 450/532 nm	Lm HgCdTe APD; Gm InGaAs APD; PMT (to ~ 1.4 μm) MCP (to ~ 900 nm)	Lm HgCdTe APD HgCdTe FPAs SL/nBn FPAs
Aperture	>1.5-m aperture; areal density <25 kg/m^2	>1.5-m aperture; areal density <25 kg/m^2	>1.5 m aperture; areal density <25 kg/m^2	>1.5-m aperture; areal density <25 kg/m^2
IT*	Sub-μm HPC hardware and tools; intelligent sensor management for laser life optimization	Sub-μm HPC hardware and tools; intelligent sensor management for laser life optimization	Sub-μm HPC hardware and tools; intelligent sensor management for laser life optimization	Sub-μm HPC hardware and tools; intelligent sensor management for laser life optimization

* Cross-cutting across multiple measurements and sensor modalities.

Preliminary Conclusions and Recommendations

<u>Conclusions</u>

- 1 μm bulk solid-state (BSS) laser technology and associated harmonic generations to VIS/UV are fairly mature
  - *Development needed for reliability, continuous improvement of WPE of base laser technology*
  - *Development specifically needed durability and reliability of UV harmonic generation (wavelengths < 400 nm).*
    - NLO materials and crystal coatings are improvement areas

- 1 μm fiber-laser technology is rapidly approaching BSS laser technology for P_{ave} and linewidth performance, lags in P_{pk} and low PRF parameters. Harmonic generations to VIS/UV are fairly mature.
  - *Waveform agility a priority for a range of national security lidar applications, development of waveform generation infrastructure progressing to relatively advanced stage*
  - *Fiber technology development needed to scale peak power capability at 1 μm*
    - Large mode area fiber and new glass compositions will be key

Preliminary Conclusions and Recommendations

Conclusions

- Telecom-type single-mode laser diodes and optical amplifiers are well-established at 1480-1625 nm and ~ 1000 nm λ (Nd^{3+}, Yb^{3+}); emerging in 1625-2000+ nm range
  - *Continued Development needed for reliability, improvement of WPE for established ranges*
  - *1625-2000+ nm signal lasers currently have low power, optical amplifiers lacking or at early stage of development.*

- 1.5 and 2 μm BSS and fiber-laser technology is in varying stages of development.
  - *High power fiber-MOPA performance in Tm-fiber rapidly advancing*
    - Large mode area fiber and new glass compositions will be key, led by technology start-ups
    - 793 nm pump diode technology fairly mature, longer λ pumps in development
    - Signal diodes and semiconductor amplifiers relatively immature
  - *High power fiber-MOPA performance in Er-fiber lags*
    - Product base strongly oriented to telecom performance requirements. Large mode area and PM fibers not nearly as widely available as in Yb-fiber
    - Pump diodes on the order of 30-35% electrical efficiency

Preliminary Conclusions and Recommendations

<u>Recommendations</u>

- *Photonic Integrated Circuits* (PIC's) represent opportunity to consolidate signal generation, amplification, frequency/waveform formatting with significant SWaP improvements
  - *Development of monolithic and heterogeneous Integrated Photonic modules is well established in 1550 nm telecom band, emerging at 1000 nm and 1800-2000+ nm*
- *Pump diode development needs to continue* for improved electrical efficiency and reliability in 790-1000 nm range, especially at wavelengths needed for direct-pumping Er, Tm, Ho.
- *Investigate fiber/BSS hybrid technologies*. Potential solutions to difficult performance and wavelength requirements
  - *At high PRF fiber-based MO+preamp subsystems or fiber-MOPAs enable significant SWaP benefits and potentially unprecedented waveform agility*
    - Especially true for 1020-1100 nm, 1500-1600 nm, 1800-2100 nm wavelength ranges
    - Development of new glass hosts and new fiber designs should continue
  - *At lower PRF* (< 10 kHz) *fiber-based systems/subsystems probably require development for QCW-pumping and ASE/nonlinear penalty control and mitigation*
- Although good nonlinear optical (NLO) materials are available for many measurements requiring harmonic and parametric wavelength conversion, NLO materials for 200-400 nm and 1600-2700 nm ranges can be improved
  - *AR coatings and NLO crystals suffer from environmental and damage susceptibilities, and continued development is needed*
  - *Quasi phase-matched material development in lithium niobate, lithium tantalite, GaAs should continue for power scaling, efficiency optimization, robustness*

Performance Needs References

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- **Receivers State-of-the-Art and Future Requirements**
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Receiver Assessment for the 2007 Decadal Survey Measurements

Capability Gap	Measurements	TRL	"Greatest Challenge" TRL
High-efficiency detectors in 1.5-2 micron range	CO_2 (ASCENDS)	5	Space qualification/ radhard assurance
Field-widened interferometric receiver	Aerosol/Clouds/Ecosystems (ACE)	4	Wavefront error
High-bandwidth, high-sensitivity detector arrays	3D Biomass (NISAR/GEDI, formerly DESDynI)	5	N/A
None	Gravity (GRACE II)	6	N/A
Multiple aperture/beam receiver	Topography (LIST in 2007 Decadal)	3	Large-area detector with high readout b/w
Single telescope supporting multiple look angles	3D Winds	3	Large-aperture receive optics (HOE/DOE, interferometer)

Enabling Technologies for New Measurement Concepts

Capability Gap	Concept	TRL	"Greatest Challenge" TRL
Detector performance	Phytoplankton	2	Dead-time, afterpulsing
Detector performance	Ocean Mixed Layer	2	Dead-time, afterpulsing
Low-noise, few-photon-sensitive detector array	Non-CO_2 Green House Gases	5	Space qualification
Large-aperture collector; detector efficiency	Ozone	4	Deployability
Detector performance	Water vapor profiles	4	Low-noise, photon-sensitive detector array

Technology Areas 2016

Technical Area	2006	2016	Rationale
Alignment Maintenance	X	**X**	Cross-cutting technology.
Scanning Systems	X	**X**	Cross-cutting technology for measurements requiring multiple look angles or specific look angles on command
Large Effective Area, Light-weight Telescopes	X	**X**	Cross-cutting technology for virtually all measurements
Mechanical Metering	X	**-**	No quantitative requirements were levied
Specialty Optics	X	**X**	Cross-cutting component
Narrowband Optical Filters	X	**X**	Core technology for each measurement
Detectors and Amplifiers	X	**X**	Core technology for each measurement
Optical High Resolution Spectral Analyzers	X	**X**	Needed for HSRL systems to ocean profiling, aerosol
Detection Electronics	X	**X**	Cross-cutting technology
Cryocoolers	-	**X**	Required for low-noise, high QE detectors in the NIR/SWIR/MWIR (e.g., HgCdTe Lm-APD)

Observations

- **Alignment maintenance is generally still challenging at the ~5-10 μrad regime, but significant improvements have been made in the past 10 years**
  - *ICESat-2 ATLAS will meet 2006 requirement for altimeters when launched*
  - *Has not been demonstrated for smallsats*
  - *Implementation at this level is primarily an engineering challenge and not a technology development effort, with the exception of a few areas (i.e., lag-angle compensation, SWIR)*
- **Cross-cutting technology: large, light-weight apertures**
  - *Power-aperture product: larger apertures or higher power lasers (or both)*
  - *Current SOA space-based telescopes are 1-2 m diameter*
  - *Lighter-weight, cost-effective apertures in the 1-2 m range would improve system SWaP trades (additive manufacture)*
  - *Deployable apertures larger that >1.5-2 m would enable reduced laser power or improve system performance*
  - *Smaller deployable apertures could enable some missions from smallsats*

Observations (cont.)

- **All measurement scenarios would benefit from improved detector performance**
  - *Multi-element detectors with high QE/PDE, low noise, low timing jitter*
  - *Full-waveform capabilities and large dynamic range (single-photon to high count rates)*
  - *For cooled arrays, higher operating temp and/or improved cryocoolers needed*
    - *State-of-the-art Dewar-cooler technologies, particularly linear-drive technology, are getting as small as 5x5x5 cm and power consumption of a few watts.*
    - *MEMS-based coolers are under development*
  - *Strong belief that domestic industry base is not currently able to respond to lidar community needs for affordable, low-volume, custom detector designs*
  - *International collaboration on custom detectors challenging due to ITAR/EAR restrictions*

- **Cross cutting: additive manufacturing for improved mechanical and thermal stability, reduced size and weight**

- **As in the case of transmitters, opportunities for synergistic DoD contractor development**

Technology Needs: Alignment

Measurement	Technology	State of the Art	Requirements	Development Need
Wind	Voice-coil actuated 2-axis beam control with reference camera star-tracker and INS system	5-10 µrad co-alignment demonstrated in the Vis/ NIR for ground and airborne systems. ~5 µrad will be demonstrated in a satellite system on ATLAS with LRS. Lag-Angle Compensation: Still being evaluated; designs for ~1 µrad LAC developed, 10s of µrad demonstrated	5 microrad roundtrip (5 msec) lag angle compensation (coherent) 50 microrad active T/R boresite alignment (direct)	• Develop optical lag angle compensator • Prelaunch lidar alignment subsystem; highly quality beam reducing telescope; > 50 cm diameter for space application for far-field • On-orbit pointing knowledge subsystem (alignment sensor +INS) needs to be demonstrated at 2 micron. Needs high-efficiency, high-sensitivity SWIR star tracker, high temp (TEC or room temp.) • Develop active optical boresite alignment device
CO_2			50 microradian standard deviation on a zero mean Maintain transmit/ receive overlap on the signal detector(s) to within 10% of ideal	On-orbit pointing knowledge subsystem (alignment sensor +INS) needs to be demonstrated at 2 micron. Needs high-efficiency, high-sensitivity SWIR star tracker, high temp (TEC or room temp.)

Technology Needs: Scanning Systems

Measurement	Technology	State of the Art	Requirements	Development Need
Wind	*Still under review*	TWiLiTE telescope uses a 40 cm diameter HOE as the receiver collecting and focusing aperture	30 deg nadir angle wide field of view telescope designs	Develop >75 cm holographic or diffractive optic telescope and step stare rotating mechanism including momentum compensation.
Topography	Polarization Gratings (cycloidal diffractive waveplates) *and/or* SEEOR (LC-clad waveguide) Switchable fiber arrays	SEEOR: Vis-NIR operation, 60x15 degree FOV 2D scan GFSC has demonstrated benchtop fiber array for FOV selection	addressable FOV across 1 - 2 degrees	Develop solid-state approach of selecting individual fields-of-view at high switching rates.
Wind, Topography, T and Water	*Still under review*	10 cm devices with acceptable efficiencies have recently been demonstrated.		Non-mechanical large aperture (> 25 cm) beam steering and receiver pointing devices.

Technology Needs: Telescopes

Measurement	Technology	State of the Art	Requirements	Development Need
Wind, Aerosols	Beryllium or SiC Field lens-corrected Ritchey-Chretien or other Cassegrain receive telescope	Single aperture, 1-1.5 m, ~0.2-0.5 mrad FOV	Light-weight telescopes > 1 m	Light-weight, deployable telescopes > 2 m diameter*
Aerosol, Ocean, Non-CO2, Phytoplankton			2-5 meter primary mirror telescope for space based lidar, <F/1 primary, <100 micron blur circle, high transmission (>95%) at target wavelength(s), low thermal distortion, high rigidity	
Topography			1 - 1.5 m diameter, < 10 microradian blur circle	
CO_2, Ozone			3m diameter deployable, ~100 mrad FOV, areal density <25 Kg/m2	

* Aperture size requirement is dependent on transmitter.

Technology Needs: Specialty Optics

Measurement	Technology	State of the Art	Requirements	Development Need
Wind	Pure silica or Hollow-core photonic crystal fiber	Commercially available options, but may not meet requirements in both UV and Vis, may not be space qualified	Fiber couplers and fiber optics with high performance at 355 and 532, rad hardened	Improve UV rad-hard fiber couplers and fiber optics
Phytoplankton, aerosol, ocean mixed layer	Hard coated rugate or other interference filter	Meets or exceeds specification except possibly at UV edge	1-3 nm half-height or better, D > 5, 90% transmission or better in 380-800 nm range	Develop the 532 nm notch filter that meets or exceeds the specification
CO_2	SiO_2/GeO_2	PM single mode passive optical fibers are commercially available but are not rad hard, may not meet transmission requirements	Polarization maintaining, radiation tolerant 2 micron single mode fiber with transmission efficiency > 95%/m	Assess radiation hardness and improve transmission of fibers

Technology Needs: Narrowband Optical Filters

Measurement	Technology	State of the Art	Requirements	Development Need
Wind, Aerosol, Ocean	Quasi-monolithic field-widened Michelson or Mach-Zender interfero-meters	~1 degree, 25 mm aperture 0.1-1 m OPDs Demonstrated 25:1-50:1 transmission ratios with Michelson design. Wavefront error limits contrast	Increase interferometer to > 10 mrad to support large telescopes. 0.1-1 m OPDs. GHz resolution or less, Mie transmission ratio of >100:1, goal of 1000:1 to support HSRL measurement in clouds	Athermal field-widened interferometers to support larger apertures
CO_2	Hard coated oxide interference filters	Few 100 picometers FWHM, >80% T, rounded transmission peak, OD9 out of band rejection	100s of pm, >90% T, flat top profile	Stable, flat top filters need to reduce filter distortion, improve SNR
Water	*Still under review*	*Still under review*	high transmission (>80%), fast temporal response (<100 microseconds), <10-20 pm optical bandpass, large free spectral range (>100-300 pm), high contrast ratio (> 100/ contrast ratio), etendue >50mm-mrad	Tunable interferometric filter for implementation in high PRF multi-wavelength DIAL in the VIS-NIR

Technology Needs: Detectors

Measurement	Technology	State of the Art	Requirements	Development Need
Wind (direct or hybrid), Aerosol	PMTs,, Si APD, or Accumulation CCDs	PMTs, QE ~25% Si APD, >65% QE, < 300 cps DCR, < 50 ns dead time ACCD: 85% QE, 16x16 pixels, 25 x 2.1 us range gates, 7 noise e- per pixel, 16-bit ADC	Single element or array detectors with single photon counting sensitivity, QE> 50 %, internal gain 10^6, dark current <1 kcps, active area > 2 mm2	Develop and demonstrate photon counting detector arrays for increased dynamic range
Wind (coherent) CO2, non-CO2 GHG, water	HgCdTe APD arrays	80K, 2x8 pixel arrays, 75% QE, 200 kHz DCR, few photon sensitive, 10 MHz bandwidth, 400-4200 nm responsivity	Multipixel arrays, >75% QE, <200 kHz DCR, few photon sensitive, 10 MHz bandwidth, 750-3400 nm responsivity, low power consumption (<5W including cooler)	Develop and demonstrate arrays
Ocean Mixed Layer	Si APD or PMT	PMTs, QE ~25% Si APD, >65% QE, < 300 cps DCR, < 50 ns dead time	Gated on and off within 20-50 ns, high quantum efficiency (>50%, goal >70%), Excess noise factor <2 (variance domain), low afterpulsing , large dynamic range, large aperture (>1 mm^2), low dark noise, Gain 10^5- 10^6	Develop and demonstrate arrays
Topography, 3D biomass, Aerosol	Si APD or PMT (532 nm) InGaAs or HgCdTe APD (1064 nm)	InGaAs: 256x64 pixel arrays, 35% QE, < 10 kHz DCR, single photon sensitive, ~350 ps timing jitter, asynchronous HgCdTe: 80K, 2x8 pixel arrays, 75% QE, 200 kHz DCR, few photon sensitive, 10 MHz bandwidth, 400-4200 nm responsivity	Large arrays (256x256), high-efficiency (>50%), high-bandwidth (1 GHz), low-timing jitter (<100 ps) arrays with high count rates (>100 Mcps).	Low-cost, high efficiency, larger format, radiation hard photon counting arrays

Technology Needs: High Resolution Spectral Analyzers

Measurement	Technology	State of the Art	Requirements	Development Need
Phytoplankton, ocean mixed layer	*Still under review*	Although there are commercial prototypes, none of them meets the specified quantitative requirements and is a space-qualified product.	LSE detection in 520-800 nm (optional: 370-800 nm, TBD) range, 1-3 nm resolution, adjustable gating with 40-100 ns pulses synchronized with the LSE backscatter arrivals, photon counting capability, high quantum (QE) efficiency (50% or better), low noise	Develop a space-qualified LSE spectral detector/analyzer that meets or exceed the listed requirements

Technology Needs: Detection Electronics

Measurement	Technology	State of the Art	Requirements	Development Need
Wind	*Still under review*	*Still under review*	FPGA based Real time processors for LOS winds from multiple lines of sight with variable platform motion	on-board processing of sensor (e.g. Star tracker pointing + lidar Doppler shift) information into data product (e.g. wind) estimates
CO_2	*Still under review*	*Still under review*	20 MHz, 16 bit ADC	High speed, high resolution ADC
Topography	*Still under review*	*Still under review*	low power(<50W),12 bit, 1 Gsamp/s, 9 channel digitizer streaming digitizer, 1 Gsamp/s, 10-12 bit resolution with integrated pulse identification and time tagging	Develop a low power option for return pulse digitization with 10-12 bits of dynamic range at sampling rates of 1 Gsamp/s. Integrated return-pulse identification and processing is desired. Couple a high-speed A/D converter with a high-speed FPGA capable of continuous digitization and real-time return-pulse identification.

Technology Needs Trades

	UV 355-400 nm	VIS 400-650 nm	NIR/SWIR 700-2000 nm	MWIR 3-5 micron
Measurement	3D Winds; Water vapor; Trop. ozone	Physical/biological oceanography; aerosols; topography	3D Winds; GHG; water vapor; O_2; topography; aerosols	GHG (CH_4)
Transmitter	THG of 1-μm sources; multi-stage non-linear wavelength conversion	SHG of 1-μm sources; multi-stage non-linear wavelength conversion	1, 1.5, 1.8-2.6 μm sources; SHG of 1.5, 2 μm sources; OPO/OPA of 1 μm sources	OPO/OPA of 1, 1.5, 2 μm sources; narrow-gap laser diodes
Detector	**GaN, MCP, DD-CCD; Low-noise multi-element arrays, QE > 50% @ 355 nm**	**Si-APD, PMT; Gateable <50 ns, QE 50-70% @ 450/532 nm**	**Lm HgCdTe APD; Gm InGaAs APD; PMT (to ~ 1.4 μm) MCP (to ~ 900 nm)**	**Lm HgCdTe APD HgCdTe FPAs SL/nBn FPAs**
Aperture	**>1.5-m aperture; areal density <25 kg/m^2**	**>1.5-m aperture; areal density <25 kg/m^2**	**>1.5 m aperture; areal density <25 kg/m^2**	**>1.5-m aperture; areal density <25 kg/m^2**
IT*	Sub-μm HPC hardware and tools; intelligent sensor management for laser life optimization	Sub-μm HPC hardware and tools; intelligent sensor management for laser life optimization	Sub-μm HPC hardware and tools; intelligent sensor management for laser life optimization	Sub-μm HPC hardware and tools; intelligent sensor management for laser life optimization

* Cross-cutting across multiple measurements and sensor modalities.

Preliminary Conclusions and Recommendations

- **Improvements in detector performance needed for all measurement scenarios**
  - Develop techniques for radiation hardening of single-photon detectors.
  - Improved low defect/defect-free fabrication and processing techniques that result in arrays with the required pixel densities and low cross talk and dark counts
  - Expand detector dynamic ranges to support photon-number resolving and higher count rates
  - Increase detector bandwidths, match to the available transmitter PRF
  - Strengthen domestic vendor base for novel detector development
  - Leverage DoD investment next-gen detector development
- **Deployable apertures could relax requirements on transmitter technologies and enable measurement scenarios from smaller satellite platforms**
- **Reductions in size and weight for receive telescopes would benefit all measurement scenarios**
  - Dependent on system trades against receive optics train throughput, detector performance and laser transmitter power
- **Novel manufacturing and design in mechanical metering may relieve active alignment requirements**
  - **Integrated structural, thermal, and optical modeing of receive systems needed**
- **Athermal large aperture field-widened interferometers needed for wind and aerosols**

- **Transmitters State-of-the-Art and Future Requirements**
- **Receivers State-of-the-Art and Future Requirements**
- **Data Utilization and Acquisition Future Requirements**
- **Emerging Technologies and Trends**

C&DH Assessment for 2007 Decadal Survey Measurement Recommendations

Capability Gap	Measurements	TRL
Cloud detection, instrument pointing (<4 μrad), health monitoring	CO_2 (ASCENDS)	4
Instrument pointing knowledge, compression	Aerosol (ACE)	4
None (met by GEDI)	3D Biomass (DESDynI)	6
None (met by GRACE FO, Sat-to-Sat communication)	Gravity (GRACE II)	6
Onboard processing, compression, laser life prognosis (<days)	Topography (LIST)	3
Autonomous acquisition, real-time LOS wind, validation (<1hr), OSSE	3D Winds (Demo)	5

Enabling Technologies for New Concepts

Capability	Concept	TRL	Challenge
Cross-cutting	3D biomass	3	Onboard compression, calibration & validation
Algorithm	Phytoplankton	4	Event detection
Algorithm	Ocean mixed layer depth	5	Cloud detection
Technology	Non-CO_2 GHG	5	Instrument pointing
Health & Monitoring	Atmospheric composition	4	Instrument pointing, laser life prognosis

General Observations

- **Four categories of development needs**
  - *Technology*
  - *Engineering*
  - *Cross-cutting*
  - *Algorithms*

- **Engineering needs are mission specific based on instrument, power, and spacecraft**
  - *It is not feasible to start the development until phase A*

- **Cross-cutting needs require long term investment and standardization**
  - *Onboard processor and storage*
  - *Instrument interface, telecommunication, data compression*
  - *Ground data processing, data analytics*

- **Algorithms**
  - *Instrument specific*
  - *Model-specific data*

Technology Areas

- **Utilized 2006 Survey as the starting point**
- **Input received from various groups broke into the following overarching areas:**
  - *Data Collection & On-board Processing*
  - *Spacecraft Control & Communication (Data Transmission)*
  - *Ground Processing*
  - *Algorithms/Models*
  - *Enabling Technology*

Onboard Processing

- **Optimize data collection**

- **Effort is to reduce the amount of data initially collected, i.e., don't simply operate sensor in always-on mode. Use information from a variety of sources to do this, thereby reducing resource impacts downstream.**

    - *Adaptive Sensor Operations: with knowledge from another platform, another on-board sensor, the data from the active sensor or a pre-loaded dataset, automatically reconfigure the sensor collection parameters to collect the right data or the right target*
        - On-board Sensor Control
        - Standardization of Interfaces and Controls
        - Spacecraft Area Network
        - Formation Flying

    - *Science model-driven adaptive targeting*

Onboard Processing (Cont.)

- **Even with the effort to reduce the amount of data collected, data volumes are expected to continue to increase. Need to store, process, and compress it on-board to meet various mission needs.**
  - *On-board Storage*
    - Space-qualified Terabyte storage Hardware
  - *On-board Processing*
    - Space-qualified HPC HW & programming tools
    - On-board near real-time data processing
    - Real-Time wind profiles
    - Mission error Budgets
  - *Software Compressive Sensing*
- **On-Board Data Compression**
- **Development of compression algorithms to reduce the amount of data retained and transmitted. Development of "policy" on the use of lossy compression – is it ever acceptable not to transmit/archive the original data?**
  - *Space-qualified HPC HW & programming tools*
  - *Data Compression: Lossless*
  - *Data Compression: Lossy*

Onboard Processing (Cont.)

- **Health Monitoring & Control**

- **Need both autonomous on-board sensor health monitoring & correcting capabilities, combined with the use of "ground truth" data from both airborne and ground-based lidar systems for calibration and data validation.**

    - *Intelligent sensor health & safety*
    - *Airborne lidar validation systems*
    - *Ground lidar validation systems*

- **Pointing & tracking**

Spacecraft Control and Communication

- **Transmit (& Receive) the Data**
- **A platform/sensor can be expected to transmit data to another on-board sensor, to another satellite or to the ground. Standards and protocols need to be established to facilitate. Quantity of data is continuing to increase, advanced data transmission capabilities need to be developed (i.e., laser communications). A platform can also be either producer or consumer of this satellite-to-satellite data.**
    - *Transmit the data to another Sensor*
        - Standardization of Interfaces & Protocols
    - *Transmit the data to another Satellite*
        - Standardization of Interfaces & Protocols
    - *Transmit the data to Ground*
        - Large Volume Data Downlink: Laser Communications

Ground Processing

- **Ground Systems**

- **Once the data has been transmitted to the ground, it must support various levels of processing: near real-time Decision Support Applications, Science Products and further science research.**

  – *Knowledge Discovery*

  – *Cloud-based Processing*
    - Establish cloud-based service oriented architecture for processing data once it reaches the ground allows for rapid expansion and contraction of capacity eliminating the need to maintain large local processing clusters for each mission.

  – *Storage & Archive*
    - Data Management/Service Oriented Architecture
    - Cloud-based Storage: Establishing cloud-based storage capability will allow cloud-based data holdings to be published to a variety of architectures as a service. Raw data can be archived to offline storage, while processed (more actively used data/products) can be maintained online for faster access.

Ground Processing (Cont.)

- **Data Dissemination**

- **Data delivery should be flexible enough to provide the requestor with the exact data and metadata needed, in the format needed. Additionally, the ability to provide online visualization of data should be a part of the concept of operations, if the data content allows.**

    - *Data Compression: Lossless*
    - *Data Compression: Lossy*
    - *Data Visualization*

Algorithms/Models

- **This is not a technology development. Most of the development needs should be addressed by mission and ROSES R&A**

- **Modeling**
  - *Observation System Simulation Experiments (OSSE)*
  - *Model lidar data resampling techniques*

- **Algorithms**
  - *Instrument specific algorithms and theories*
  - *Ancillary data processing*
  - *Calibration and validation campaigns*

Enabling Technologies

- Cloud detection – optimization of compute intensive processing
- Coordinate sensing and event detection – onboard real-time data architecture
- Onboard processing and storage – space qualification of device technology
- Laser life prognosis – laser characterization, interactive sensing based on event detection

Emerging Technology Trends

- **FPGA**
  - *IBM Coherent Accelerator Processor Interface (CAPI), PCIe*
  - *Xilinx Virtex-5QV; Microsemi RTG4; Xilinx Zynq (non-rad-hard processor plus FPGA) Future Interface technologies; JEDEC JEDS204B high-speed serial interface ADC/ DAC converters.*
- **MEMEX**
  - *Grobid (GeneRation Of BIbliographic Data machine learning framework)*
  - *Apache Tika (detects and extracts metadata and text from over various file formats)*
  - *NLTK (natural language toolkit)*
- **CARACAS – onboard Control Architecture for Robotic Agent Command and Sensing**
- **Observations for model intercomparison projects (obs4MIPs)**
- **Cloud computing and network**

C&DH Capability Advancement Recommendations

- **Establish testbed in order to test onboard capabilities**
- **Cross-cutting needs**
  - Address instrument specific interfaces and requirements
- **Quantitative goals are needed to address Instrument specific compression and innovative retrieval algorithms**
  - Free flyer vs. hosted payload, processing power, platform specific
- **Establish calibration and validation sensor network for remote sensing instruments**
- **Sample/synthetic data needed to test processing algorithms**

Quantifying C&DH Capability

Capability	Instrument/Platform Specific	Quantitative Goal
On-board sensor control	Data latency, algorithm, Processing power	<3hr, FPGA Virtex 5
Spacecraft area network	Formation control and knowledge, bandwidth	<wavelength/2, LOS, Ka vs. X
On-board processing	Cloud screening, event detection (e.g. storm/storm front, fire), water vapor estimation	% clouds along with confidence, <3hr for weather events Water vapor: <10% uncertainty @ 500m range resolution
On-board compression	FFT, image, buffer management	10:1, 7000 MIPS*
Intelligent sensor health & safety	Life time estimation, monitoring	Catastrophic parameter detection < 1 hour
Point and tracking	Attitude control	Integrated tracking sensors < 4 microrad
Ground Processing	Network, cloud computing	Capability will be met by NISAR and SWOT (1700 nodes, 26 Gbps, 150 Pbytes storage)

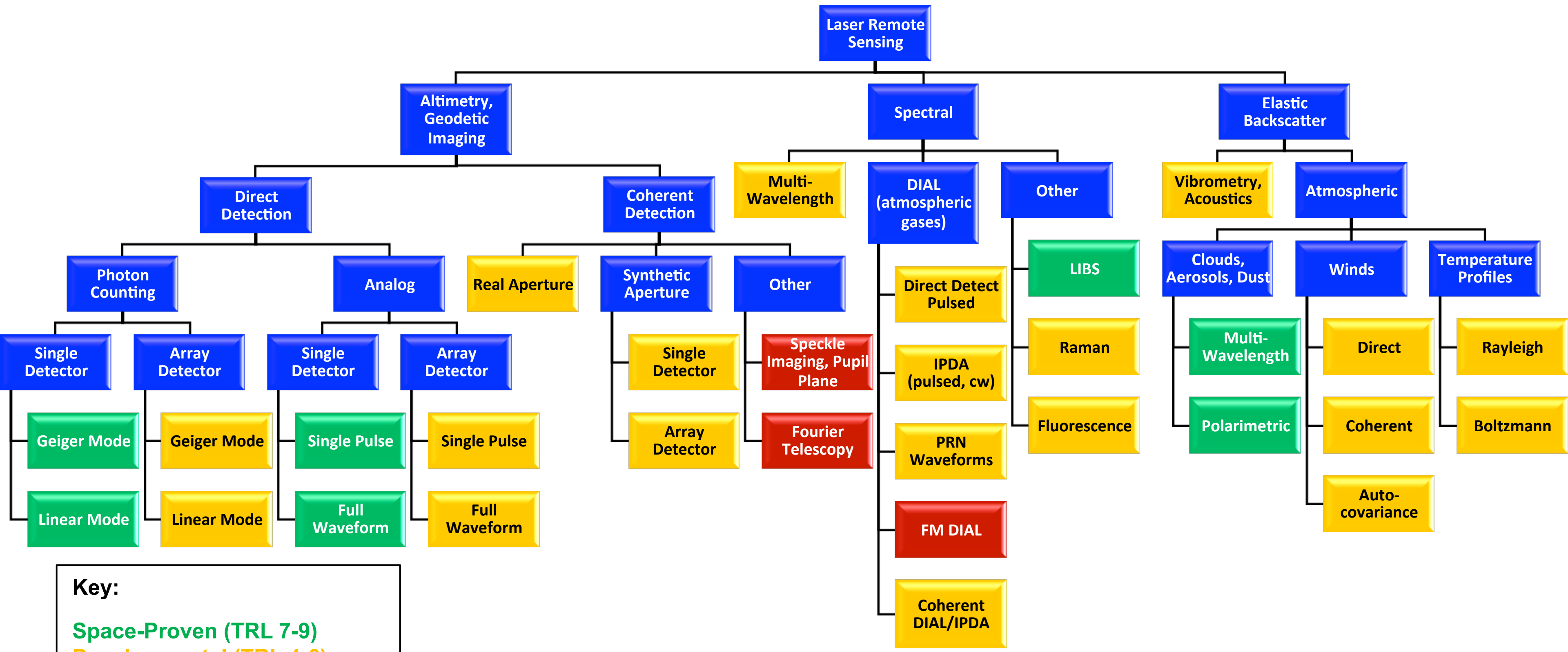
* To process 300-MB raw file in 5 seconds.

Preliminary Conclusions and Recommendations

- **Measurement requirements must be clearly defined.**
  - Quantitative requirements then follow
- **Technology requirements for each measurement in the areas of transmitters, receiver systems, and DADU/C&DH are tightly coupled.**
  - Subsystems are not implementable if top-down requirements are not defined in terms of mass, power, volume, interface, mechanical/thermal, data rate, and mission life
- **Technology development to satisfy the priority measurement(s) must then be targeted and coordinated in the three categories in order to achieve maximum return on investment.**

- Transmitters State-of-the-Art and Future Requirements
- Receivers State-of-the-Art and Future Requirements
- Data Utilization and Acquisition Future Requirements
- **Emerging Technologies and Trends**

Laser Remote Sensing Taxonomy: Space



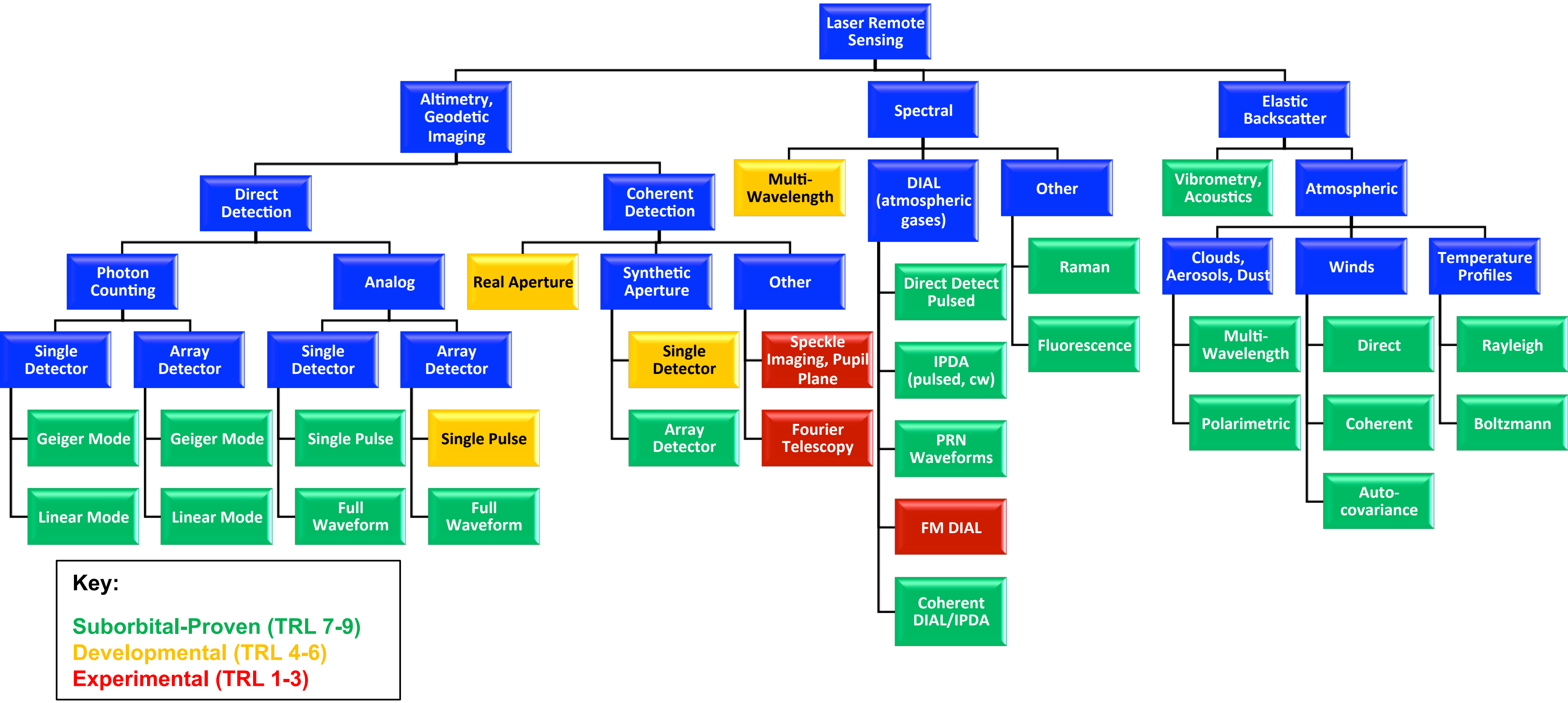
Key:

Space-Proven (TRL 7-9)
Developmental (TRL 4-6)
Experimental (TRL 1-3)

Each sensor/measurement has its own Command and Data Handling 'shadow', in addition to the cross-cutting IT challenges.

Adapted and updated from: *Laser Radar: Progress and Opportunities in Active Electro-Optical Sensing* (NRC, 2014).

Laser Remote Sensing Taxonomy: Suborbital



Each sensor/measurement has its own Command and Data Handling 'shadow', in addition to the cross-cutting IT challenges.

Adapted and updated from: *Laser Radar: Progress and Opportunities in Active Electro-Optical Sensing* (NRC, 2014).

Emerging Technology Definitions

- **Since the 2006 report there has been a revolution in smallsat/hosted payload concepts, fueled in part by an increasingly (even aggressively) cost-constrained environment**
  - *In this paradigm miniaturization is key*
  - *The burgeoning additive manufacturing field offers potential solutions for previously impossible enabling constructs (e.g., large-area mirrors that are lightweighted in ways that cannot be accomplished through other means)*
  - *Integrated photonics approaches are being used to dramatically compact optical designs*
- **The decision to actively address this emerging technologies in the 2016 report reflects a realization that new capabilities could determine the success of more stringent measurement requirements and that they should be defined and their development accelerated**
- **"Emerging technologies are technologies that are perceived as capable of changing the status quo" (*Wikipedia)***
  - *Potential game changers*
- **For the current purpose we defined emerging technologies as being at a maturity level of <TRL3**
  - *TRL 2 is the entry point for ESTO's ACT and AIST programs*
- **System engineering as an emerging technology**
  - *Trades between aperture size, detector efficiency, laser power, and waveform can mitigate technological hurdles*
  - *Requires robust, high-fidelity modeling and simulation capabilities*

Unmet Technology Needs Since Prior Decadal Survey

Capability Gap	Measurements	Current TRL
SWIR optical mux	CO_2 (ASCENDS)	2
Tunable NIR laser; High-QE UV/Vis detectors; Narrowband wide-acceptance filter	Aerosol (ACE)	1-2
Intelligent performance management	3D Biomass (DESDynI)	2-3
Demonstrated by GRACE FO*	Gravity (GRACE II)	—
Intelligent performance management	Topography (LIST)	2-3
High-QE multi-element UV/SWIR detector arrays	3D Winds (Demo)	2
Intelligent performance management; Rad-hard deep-submicron microelectronics	All	2-3

* Laser supplied by DLR (Germany).

Emerging Needs for New Measurement Concepts

Capability	Measurement	Current TRL
Intelligent performance management	3D biomass	2-3
Narrowband blocking filter; High-resolution spectral analyzer	Phytoplankton	2
Moderate PRF blue laser	Ocean mixed layer depth	2
SWIR optical mux	GHG	2
Tunable NIR laser; NIR optical mux; Photonic crystal fiber gas reference cell; Large collection aperture; Narrowband wide-acceptance filter	Other atmospheric composition (water vapor)	1-2
Tunable UV laser; Large collection aperture	Other atmospheric composition (ozone)	2
Tunable NIR laser; High-QE UV/Vis detectors; Narrowband wide-acceptance filter	Other atmospheric composition (clouds and aerosols)	1-2
Intelligent performance management; Rad-hard deep-submicron microelectronics	All	2-3

General Observations

- **Six primary categories of lidar-specific development need**
  - *Nonlinear wavelength generation in the UV thru NIR*
  - *High-QE detector arrays and fast gateable single elements*
  - *Deployable large collection apertures*
  - *Narrowband blocking filters and spectrum analyzers*
  - *Photonic integrated circuits*
  - *Performance management to maximize laser life*

- **One broad cross-cutting need that would benefit multiple other sensor technologies**
  - *Radiation hardened deep-submicron microelectronic technology*

Emerging Transmitter Laser Technologies

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
Blue laser	Ocean temperature profiles (mixed layer depth)	SHG/THG of 940/1320 nm Nd:YAG; OPO w/Nd:YAG 3rd harmonic	400-480 nm; PRF ≤ 500 Hz; 30-100 mJ
UV laser	Tropospheric ozone profiles	High-energy pumped multi-stage cascaded non-linear optical scheme	UV pairs separated by 10-20 nm; space: 305-320 nm; airborne: 290-320 nm; high efficiency, 100-1000 Hz, 20-100 mJ, M^2 <2, linewidth <1 Å, pulse width 10-30 ns
NIR laser	Water vapor and aerosol/cloud profiles	Current Ti:Sapphire lab solution not viable for space; 532-nm pumped OPO or cascaded non-linear optical scheme with high-WPE 1/1.5-μm pump laser	720 nm, WPE 5-10%, 20-40 W at 1000-3000 Hz, or 100 mJ at 100 Hz double pulsed within 200-300 microseconds, spectral purity >5000/1, pulsewidth <20 ns, linewidth <100 MHz

Emerging Ancillary Transmitter Technologies

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
Optical switches	Water vapor and methane profiles/ columns	Up to 4x1 switches exist with acceptable response time at TRL 5. Improved optical cross talk and increased input channels desired to improve spectral purity and reduce physical footprint for space applications. Need wavelength agility to execute measurement	Multi-input (4x1) switch to multiplex varying wavelength seed lasers onto a single fiber for injection seeding pulsed DIAL wavelengths (700-1000 nm, 1650 nm)
Gas reference cells	Water vapor profiles	Photonic crystal fiber gas cells in current use for spectroscopic applications, but little research dedicated to sealing the cells with a fixed amount of gas for long term unattended operation	Compact cell for water vapor DIAL laser line locking. Photonic crystal fiber that can be sealed and spliced to commercially available single mode fiber; <20 dB/km optical loss @ 760/820/940 nm

Emerging Detector Technologies

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
Detectors (Including Arrays) and Amplifiers	3-D winds	InGaAs arrays with extended response to 2 microns previously demonstrated but vendors are no longer working in this area; may require alignment of fibers to each detector element to maintain heterodyne efficiency	Multi-element arrays; QE > 80%, BW > 200MHz @ 2 microns; QE > 50%, dark counts <1 kct/s @ 355 nm; QE > 70%, dark counts <1 kct/s @ 532 nm
Detectors (Including Arrays) and Amplifiers	Aerosol profiles	Non-U.S. vendors not an option due to export control/MCTL/ITAR	Gateable within 20-50 ns, QE 50-70% @ 355/450/532 nm, low afterpulsing, large dynamic range, low dark noise

Emerging Ancillary Receiver Technologies (1/2)

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
Large Effective Area, Lightweight Telescopes (including stray light control)	Trace gas profiles	Demonstrations of deployable structures; single-petal reflector including the latch and hinge mechanisms for mechanical stability	3-m aperture with deployable mechanisms; areal density <25 kg/m^2
Specialty Optics: High Transmission Optics, Fibers, Polarization Control, Wavefront Phase Control (Mode Matching)	Phytoplankton	Iodine-filled cell	Narrow-band 532-nm notch filter to reduce laser backscatter to the level comparable with fluorescence and Raman components in the laser-stimulated backscatter signal
Narrowband Optical Filters	Water vapor & aerosol profiles	Metamaterials with large angular acceptance; volume Bragg gratings are an alternative for ~10 pm	Tunable interferometric filter for implementation in high PRF multi-wavelength DIALs operating in the VNIR (500-1000 nm)

Emerging Ancillary Receiver Technologies (2/2)

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
Optical High Resolution Spectral Analyzers	Phytoplankton	Commercial prototypes exist, but none meet the specified quantitative requirements and are space-traceable	Laser-stimulated emission (LSE) spectral detector/ analyzer; 370-800 nm, 1-3 nm resolution, adjustable gating
Photonic Integrated Circuits*	Lidar/lasercomm smallsat constellations	Utilize lasercomm components beyond lasers/ amplifiers	Dramatic SWaP reductions to enable smallsat applications; 1-2 microns

* Cross-cutting across multiple measurements.

Emerging Information System Technologies

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
Intelligent sensor health and safety*	Autonomous monitoring & control of lidar H&S (laser performance/ degradation, laser life optimization strategy)	Trim laser output power based on performance degradation tracking	Sensors for use in predicting lidar health; control software including degradation mode models and cost functions for optimizing instrument performance and/or instrument life
Space-qualified HPC HW and programming tools†	Enabling technology for smallsat and hosted payloads	Current radiation hardened technology is at 0.35 and 0.25 microns. Large investment needed to satisfy future processing needs	Radiation hardened at deep-submicron microelectronic technology (0.25, 0.18, 0.15 and 0.09 micron)

*Cross-cutting across multiple measurements.
†Cross-cutting across multiple sensor modalities (not specific to lidar).

Emerging Technology Needs Roll-Up

	UV 355-400 nm	VIS 400-650 nm	NIR/SWIR 700-2000 nm	MWIR 3-5 micron
Measurement	3D Winds; Water vapor; Trop. ozone	Physical/biological oceanography; aerosols; topography	3D Winds; GHG; water vapor; O_2; topography; aerosols	GHG (CH_4)
Transmitter	THG of 1-μm sources; multi-stage non-linear wavelength conversion	SHG of 1-μm sources; multi-stage non-linear wavelength conversion	1, 1.5, 1.8-2.6 μm sources; SHG of 1.5, 2 μm sources; OPO/OPA of 1 μm sources	OPO/OPA of 1, 1.5, 2-μm sources; narrow-gap laser diodes
Detector	GaN, MCP, DD-CCD; Low-noise multi-element arrays, QE > 50% @ 355 nm	Si-APD, PMT; Gateable <50 ns, QE 50-70% @ 450/532 nm	Lm HgCdTe APD; Gm InGaAs APD; PMT (to ~1.4 μm); MCP (to ~900 nm)	Lm HgCdTe APD; HgCdTe FPAs; SL/nBn FPAs
Aperture	3-m aperture; areal density <25 kg/m^2	–	3-m aperture; areal density <25 kg/m^2	–
IT*	Sub-μm HPC hardware and tools; intelligent sensor management for laser life optimization	Sub-μm HPC hardware and tools; intelligent sensor management for laser life optimization	Sub-μm HPC hardware and tools; intelligent sensor management for laser life optimization	Sub-μm HPC hardware and tools; intelligent sensor management for laser life optimization

* Cross-cutting across multiple measurements and sensor modalities.

Preliminary Conclusions and Recommendations

- **Cross-cutting technologies were identified that are relevant to component and subsystem miniaturization**
  - *Each constitutes a waypoint on the smallsat/U-class constellation roadmap*
  - *Photonic integrated circuits*
    - Enables large reductions in optical system SWaP
    - Applicable across the spectrum of lidar and lasercomm concepts
  - *Rad-hard, deep-submicron microelectronics technologies*
    - Requires large investment need
    - Payoff reaches beyond lidar applications into all other sensor modalities
- **System engineering as an arbitrator between technology options**
  - *Trades between aperture size, detector efficiency, laser power, and waveform can mitigate technological hurdles*
  - *Requires robust, high-fidelity modeling and simulation capabilities, in both the environmental and sensor performance domains*
- **Need to develop and mature U.S. industrial base required for critical system components**
  - *Detectors*
  - *Laser media and nonlinear conversion materials*

Overview of NASA ESTO Microwave Remote Sensing Investment Strategy Update Community Forum

March 17, 2016

Purpose of the ESTO 2016 Microwave Strategy Update

- The last ESTO Microwave investment strategy is more than a decade old. State of the art has progressed and new areas have been entering the scene (e.g. miniaturized instruments, multi-frequencies)
- Update strategy by identifying and summarizing key technology requirements and performance parameters based on measurement themes:
  - Atmospheric composition
  - Carbon & Ecosystems
  - Climate Variability & Change
  - Earth Surface & Interior
  - Water & Energy Cycle
  - Weather
- Opportunity for community to give input and play a role in shaping ESTO's future investment strategy

How will the final report be used?

- Use the input for upcoming ESTO AOs to inform ESTO's investment strategy
- Inform the Decadal Survey on the status of technology maturity
- Seek partnership opportunities with other agencies, industry, academia
- Identify emerging new technology trends and help infuse them into existing and future concepts

Microwave Technology Community Forum

- State-of-the-Art and Future Requirements in Radar
- State-of-the-Art and Future Requirements in Microwave Radiometry
- Data and Information Processing Future Requirements
- Emerging Technologies and Trends

- **State-of-the-Art and Future Requirements in Radar**
- **State-of-the-Art and Future Requirements in Microwave Radiometry**
- **Data and Information Processing Future Requirements**
- **Emerging Technologies and Trends**

Radar Assessment for the 2007 Tiered Decadal Survey Measurements

Capability Gap	Measurements	TRL	“Greatest Challenge” TRL
Ka-band phased array	Water surface topography (SWOT)	6	High phase stability Ka-band electronics
Ka, W-band scanning	Aerosol, cloud (ACE)	4	Closely spaced multi-band active feed array
X-, Ku-band feed array	Snow Cover (SCLP)	5	Multi-band feed
None	Soil Moisture (SMAP)	9	N/A
None	Surface deformation, ice (NISAR, formerly DESDynI radar)	6	System integration & test
High efficiency solid state amplifiers	Ocean wind vector (XOVWM)	5	Dual-band single instrument

Technology Needs for Future Measurements

Capability Gap	Measurement	TRL (Respondents)	"Greatest Challenge" TRL
Very large antennas	weather radar, hazard monitoring	2-9	Mass, deployment, highest frequency band
G-band technology	Humidity profiles	2-4	Transmit power generation
SoOp technology	Ocean wind vector, soil moisture, RFI detection for radiometers	3	Wideband tunable receiver
CubeSat / SmallSat radar technology	Precipitation, other	2-5	Antenna size, thermal. Power and data rate
Fully integrated single-chip MMIC T/R modules	All	3-5	Efficiency, T/R isolation
Improved High Power Amplifiers for high frequencies (Ka-,W-, G-bands)	Cloud profiles, rain droplet size, humidity profiles, atmospheric gases	2-6	Power supply reduced mass and size; improved efficiency; improved maximum RF power
Space-qualified, high bandwidth & nbits, integrated digital subsystems	All	4-9	Reduce risk and perception of risk going from non-space to space applications.

Technology Areas 2016

Technical Area	2004 Report	2016 Report	Rationale
T/R modules	X	X	Key component for virtually all measurements
MMIC Devices	X	X	Mass and size reduction
High Power Amplifiers	X	X	Enabling for high frequency measurements
RF power, control, signal distribution	X	Drop	Mature
Waveform generators	X	X	Space qualify advanced waveform generators
Rotating Reflectors	X	Drop	Mature
ADCs for DBF	X	X	Reduce mass & power
Membrane antennas	X	X	Potential for array mass reduction
Adaptive waveform sensing	X	X	Potential for array mass reduction
SoOp		X	New measurement area
CubeSats / SmallSats		X	New measurement area
G-band technology		X	New measurement area
Digital signal generation, beamforming & receiver		X	Mass & power reduction

Specific Observations: Radar Electronics & Antennas

- L-, C-, X-band technology is mature
  - SMAP, NISAR, RadarSat II, TerraSAR-X
  - Future development should focus on technologies that will reduce cost for follow-on systems

- Many technology needs are related to phased array antennas or array feeds for reflectors
  - Array-fed reflectors do not all benefit from smaller/lighter T/R modules
    - Number of modules is smaller
    - Heat dissipation better for larger modules
    - Exception: multi-band array feeds
  - Single-chip MMIC based T/R modules at all frequencies
  - T/R module transmit efficiency, noise figure, T/R isolation
  - Line feed for parabolic cylinder reflector
    - Enables 1D electronic scanning for cloud / precipitation measurements
  - Digital beam forming for P-band phased array

Specific Observations: Radar Electronics & Antennas

- Dual/multi-band technology enables many measurements
  - Common antenna, electronics may reduce cost
- High structure mass limits practical use of phased arrays
  - Lightweight, small T/R modules do not solve problem
  - Use of phased arrays will require development of lightweight structures
    - Membranes, meshes, shape memory polymers
      - Thermal control
      - Power distribution
      - Small lightweight T/R modules to enable roll/fold up
    - Adaptive wavefront sensing for non-rigid structures
      - Computationally intensive for high frequencies

Specific Observations: Radar Electronics & Antennas

- Synergistic DoD Contractor development
  - *DARPA Innovative Space Based Radar Antenna Technology (ISAT) – Program had goal of developing 300 m long electronically steerable antenna for MEO based X-band Ground Moving Target Indication (GMTI) radar*
    - *Most work focused on development of large deployable structures*
    - *Boeing, Northrop Grumman, Lockheed Martin were prime contractors*
    - *Raytheon, Harris were radar payload subs*
    - *Program funded from 2002 – 2007*
    - *Ref: J. Guerci, E. Jaska, IEEE International Symposium on Phased Array Systems and Technology, pp 45 – 51,14-17Oct2003.*
  - DoD phased array technology
    - *Many airborne radars using phased array antennas*
    - *DARPA Arrays at Commercial Timescale (ACT) program*

Challenges

- Transmit power at high frequencies
  - *EIKAs – reducing high voltage power supply mass, improving efficiency*
  - *Improving SSPA efficiency*

- Dual/multi-band feeds/antennas that enable the same coverage at different bands
  - *Common antenna, electronics covering dual band*
    - *E.g. Harris current sheet array feed*

- Understanding technologies that enable new measurements

– *E.g. multiple look angles, tomography*

- Understanding measurement limitations for emerging radar technologies
  - *Signal-of-Opportunity based bistatics*
  - *CubeSats, SmallSats*

Challenges

- Significant SWAP reduction
  - *Most system concepts are high SWAP and very expensive*
  - *Planned technology development will result in small, incremental improvements*
    - *Unlikely to significantly reduce cost*
    - *Possible exception: cubesat-inspired new architectures have potential to significantly reduce mass and number of parts, subsystems and interfaces.*

- New technology insertion
  - *Lightweight array structures may enable use of electronically scanning phased arrays instead of reflectors*
  - *Need to understand benefit to measurement*

Radar Technology Needs Summary

Band	VHF/P L C X Ku Ka W G
Measurement	soil moisture ocean wind vector surface water topo humidity ice snow hydrometeor biomass surface deformation weather precipitation clouds
Antenna	large lightweight structures dual/multi band array feed single-chip MMIC T/R module single-chip MMIC T/R module DBF lightweight reflectors
Amplifier	HPAs – lighter, smaller, higher efficiency GaN SSPA for higher efficiency
Payload Electronics	space-qualified, high bandwidth & nbits, integrated digital subsystems
System	explore measurement enhancements from using lightweight phased arrays applying cubesat technology to larger sats SoOp systems

Preliminary Conclusions and Recommendations

Conclusions

- Dual/multi-band technology enables several measurement scenarios and has not received as much focus as it should
- Many technology needs are related to array feeds for reflectors
- Development of higher power, space qualified high power amplifiers and T/R module transmit amplifiers are most important at higher frequencies (Ka, W, G-bands)
- Signals-of-Opportunity and CubeSats both present new opportunities although specific measurement scenarios have not been fully determined
- MMIC based T/R modules have most value when there is a need for smaller, lighter modules
- Development of digital technology will enable mass & power reduction
- Ka-band has largest number of measurements
- Up-front system design trades are essential for determining technology needs

Preliminary Conclusions and Recommendations

Recommendations

- Develop a better understanding of the benefit of specific technology needs
  - Focus on technology development that will lead to significant cost reduction
  - Where technology development will enhance performance, quantify the improvement
- Develop measurement concepts for SoOp and cubesats to better understand their value
- Develop integrated dual/multi-band technology which potentially can reduce cost

Microwave Technology Community Forum

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Passive Microwave Assessment for the 2007 Tiered Decadal Survey Measurements

Capability Gap	Measurements	TRL	"Greatest Challenge" TRL
High-frequency low power Radiometers	Wet Path (SWOT)	6	High performance low SWaP radiometers to ~250-GHz
Broadband Spectrometer	UA Chemistry (GACM)	5	High performance RF Front-ends at 500 – 600 GHz
None	Snow Cover (SCLP)	7 - 9	N/A
None	Soil Moisture (SMAP)	7 - 9	N/A
High spatial and temporal resolution sounding - GEO	Precipitation Atmospheric Temperature/ Humidity (PATH)	6	V-/G-band GeoSTAR system
High spatial and temporal resolution sounding - LEO	PATH	5	Low Cost Microwave spectrometers on CubeSats

Enabling Technologies for New Measurement Concepts

Capability Gap	Measurement Concept	TRL	"Greatest Challenge" TRL
Concurrent Radar and Radiometer measurements; wide range of radio frequencies	Precipitation, Root Zone SM, SSS, Air-Sea Flux/Sea Ice and Ocean Altimetry measurements	4	Integrated Radiometer & Radar transmitter (P- L- S-band; K-Ka-band; Ka-G-band)
Polarimetric Radiometry from L- to SMMW	Ocean Surface Winds; high spatial resolution phenomena	3 - 7	Microwave polarimetry at W-band and above (lower TRL for higher frequencies)
Low SWaP-C G-band heterodyne receivers	High repeat atmospheric water vapor and temperature profiling	6	Low Power: <50mW; Low Mass: 100g; low power LOs
P-band radar/radiometry with additional bands	Root-Zone Soil Moisture	4	Wide bands at low frequencies (P-band); spectrum sharing technology
Super-heterodyne receivers; 500 – 600 GHz + G-band (SWaP-C)	Trace gasses; atmospheric water and temperature profile	3	100mW; 200g; 300 K T_{sys} at ~80 K
SWaP-C of G-band WV profiling radiometers	Tropospheric winds from repeat pass WV radiometry	5	Technique needs to be proven; requirements for low-cost sensor still TBD (Technology TRL is high)

Enabling Technologies for New Measurement Concepts

Capability Gap	Measurement Concept	TRL	"Greatest Challenge" TRL
Dual polarized radiometers operating at 89 - 650 GHz;	Cloud Ice, tropospheric water characterization	2 – 5	Low power, 0.5W/size to fit in a focal plane/feed array; low BW (2%) filters; Lower TRL for higher frequencies
Low cost atmospheric sounding for 'high volume' use in small platforms	Clouds and precipitation processes – high temporal	4	300K T_{rec}; up to 183-GHz; <50mW; <100g
2m class deployable antenna	Improved HSR for traditional measurements from low cost/ small platforms	3	Performance to ~600 GHz; stowed volume ~ 2.5U
Broadband well-calibrated frequency agile radiometer	Imaging radiometer coverage in environments with increasing RFI	4	25 kHz band segments from 1 – 50 GHz
P- to K-band feed array for large reflector	Root Zone Soil Moisture	5	Radiometer FE to fit within a specialized feed array
Direct SI traceability; Distributed Cal for STAR; Calibration of UAV radiometers	Radiometer Calibration	4	Blackbody standards & analysis; Stability of distributed Cal; (SM) System-based approach to Cal;

Enabling Technologies for New Measurement Concepts

Capability Gap	Measurement Concept	TRL	“Greatest Challenge” TRL
Broadband/Multiband FPA feed technologies to support ~7m aperture antennas	Spatial Resolution Improvements to OSW, Cloud Liquid, Precipitation, Integrated Water, Snow Cover etc.	4	10-1 band feeds with high beam efficiency and surface factor to W-band;
Large deployable antenna (e.g. D >= 10m and f =< 40 GHz)	Ultra-high spatial resolution for imaging below 40 GHz	3 - 5	>90% beam efficiency; mods to existing commercial antennas
SMMW Receiver Technology: Instrument front-ends (including LNAs); filters; detectors; calibration noise sources and switches; isolators	Cost effective high temporal sampling of precipitation, clouds, and ice	2 - 5	5dB NF from 200 – 1000 GHz (High TRL); filters to allow SSB operation at 10% BW (Low TRL); Direct detection at <100K added noise temperature (Mid TRL)

Technology Areas 2016

Technical Area	2004	2016	Rationale
High Frequency Radiometers	X	**X**	Core technology enabling measurements from smaller low cost platforms
Miniaturized and multi-frequency radiometers	X	**X**	Core technology technology for measurements requiring multiple frequencies or combination with Radar
RFI Mitigation (S/W & H/W)	X	**X**	Increasingly important to maintain measurements
Radiometer Calibration	X	**X**	Expanded to include SI-standard and UAV-based sensors
Polarimeters (L- W-band)	X	**X**	OSWV and Cloud Ice;
Combined Active/Passive FEs	X	**X**	Core technology for many measurements
2m deployable (<350 GHz)	-	**X**	Crosscutting – improvements in SWaP-C; HSR
6m class antennas (<100 GHz)	X	**X**	Crosscutting – enables improvements to HSR
10m class antennas (<40 GHz)	X	**X**	Crosscutting – enables improvements to HSR
Cryocoolers	-	**X**	Cloud Ice / high frequency radiometer performance

Observations

- **Need for radiometric measurements > 200-GHz to 1000-GHz will drive LNA and radiometer front-end technology developments**
  - *Ice Cloud characterization mission require higher frequency observations and shorter revisit times driving lower costs and implementation on multiple (small) platforms*
  - *Low SWaP-C drives investigation into direct detection approaches to 1000 GHz*
  - *Alternate approaches involve heterodyne designs with concentration on low power LOs*
  - *Better performance will benefit many areas including atmospheric and water vapor sounding*
- **Measurements requiring multi-frequencies and/or multi sensors drive many cross-cutting technology investments**
  - *State-of-the-Art is separate receiver chains and use of multiplexers*
  - *Approach to achieve adequate RF isolation*
  - *Packaging multi-frequency feed structures and RF front-ends*
- **RFI Mitigation**
  - *Continues to drive technology investment due to increasing impact to passive measurements*
  - *Better algorithms to achieve better detection and frequency agile hardware to perform measurements where no anthropogenic sources are detected or exist*

Observations (cont.)

- **Antennas: Larger or deployable apertures for traditional operating frequencies**
  - *Deployable antennas to overcome diffraction limit from systems required to fit within cubesat dimensions (up to 2m diameter aperture from 2.5U stowed configuration)*
  - *6m class antennas with higher operating frequencies (up to 100 GHz)*
  - *10m diameter or larger antennas using SMAP frequencies up to 40 GHz*
- **Antennas: Shared aperture using multi-frequencies and/or multi-sensors (Active, Passive and SoOp)**
  - *Focal plane array configurations accommodating multiple sensor front-ends*
  - *Multi-frequency feeds (e.g. cylindrical parabola)*
- **Polarimetry**
  - *Polarimetric radiometers operating above Ka-band (up to submillimeter wave frequencies)*
- **Thinned aperture radiometers**
  - *2D STAR sensors to support PATH is still relevant (TRL 6) and both competes with and complements LEO constellation approach*

Technology Needs: High Frequency Radiometers

Measure-ment(s)	Technology	State of the Art	Requirements	Development Need
Cloud Ice; Precipitation	High frequency receiver front-ends operating from 89-GHz up to >800-GHz	183-GHz LNAs @ 500 K noise temperature; frequency; down conversion; DSB configuration with filtering to achieve 3-5 separate offsets from 183-GHz line. Passive front-ends above ~200-GHz and noise temperature >>500 K operating at room temperature	300K noise temperature at room temp @183 GHz; Power <0.05W; Mass<100g	• Reduce mass, volume and power requirements of high frequency radiometers • Low Power LOs • Filtering at primary frequency of operation • Wideband receivers (multi-band backends) • Sufficiently small enough to fit within a single focal plan
Atmospheric Chemistry	High frequency receiver front-ends operating from 500- to 600-GHz	Passive front-ends above ~200-GHz and noise temperature >>500 K operating at room temperature	MMIC-based superheterodyne integrated receivers: 300K @ 20K, 500 GHz Power: <0.1W; Mass<200g	• Continued improvement of performance and f_{MAX} for high frequency InP LNAs • Performance under cryo-cooling may become an option • Low NF and noise stability are primary metrics

Technology Needs: Integrated Radiometers with Radar Transmitters and Receivers

Measure-ment(s)	Technology	State of the Art	Requirements	Development Need
Precipitation	*Under review*	High power switching; frequency multiplexers with individual receiver chains	Instrument Front-end (small SWaP); 1 unit on a small platform operating with many platforms: Power: 10 – 30W; efficiency 40%	Single unit on a small platform
Root Zone Soil moisture/ SSS/ Air-Sea-Flux/ Sea Ice	*Under review*	High power switching; frequency multiplexers with individual receiver chains	Instrument Front-end; stable internal calibration	Coexistence with Radar unit; single instrument front-end .
Ocean Surface Winds/ Altimetry	*Under review*	High power switching; frequency multiplexers with individual receiver chains	*Still under review*	Integrated polarimeter and radar receivers

Technology Needs: RFI Mitigation

Measurement(s)	Technology	State of the Art	Requirements	Development Need
Root Zone Soil Moisture	Broadband tunable notch filter; spectrum sharing technology	*Still in review*	Tunable from ~400-MHz to 2-GHz; Low loss; high selectivity	*Still in review*
Imagery over populated areas	Ultra Broadband Digital Spectrometer	3 GHz BW with CMOS 65-nm technology;	20- to 50-GHz BW; Improvements in spectral resolution; mitigation techniques	*Still in review*

Technology Needs: Radiometer Calibration

Measurement(s)	Technology	State of the Art	Requirements	Development Need
Imagery; Atmospheric Temperature Sounding;	SI Traceability (through the antenna)	SI-traceable blackbody temperature sensors – misses largest uncertainty	Techniques developed	Black body standards, traceability techniques
Atmospheric Temperature and Humidity Profiles	Distributed calibration techniques for STAR	*Under review*	Instrument front-end; stable internal calibration	*Still under review (Soil Moisture concepts)*
Imagery; high revist/ regional measurements	Calibration of UAV radiometers	Sensor and platform unique artifacts / biases requiring reprocessing before integration/assimilation	Level 3 calibrated data with minimal or no unique application-specific / platform-specific reprocessing	Combine information about ambient environment to improve unattended airborne (vs. space-based) instrument calibration
Atmospheric Sounding; Cloud Ice	183-GHz and higher noise sources for internal calibration	W-band internal noise sources are beginning to be established	Calibration stability (TBD) ENR (TBD) Low loss RF switches	*Under review*

Technology Needs: Polarimetry

Measurement(s)	Technology	State of the Art	Requirements	Development Need
OSWV, Imaging (W-band), Cloud characteristics and EPBR	High performance stable polarimetric receivers W-band and above	K_a-band (WindSat)	Polarimetric radiometers with channel-to-channel calibration; matching dual-pol radiometers	High frequency polarimetric back-ends (analog) or wideband digital back-ends
Electronic Polarization Basis Rotation (EPBR)	Internal radiometric calibration performance at W-band and above	K_a-band (TRL 6)	Enable Electronic Polarization Basis Rotation for Conical scanners	Stable noise diodes at W-band to G-band and above

Technology Needs: 2m Class deployable antennas

Measurement(s)	Technology	State of the Art	Requirements	Development Need
Precipitation; clouds: L-band through 350 GHz (lower cost alternatives)	2m deployable antenna and feeds	1.5U stowed; 0.7m aperture deployed	Surface figure: W-band: full aperture; f<350-GHz: 1m diameter Stowed volume: 2.5U	Develop and demonstrate 2m deployable reflector;

Technology Needs: 6-7m class antennas and larger

Measurement(s)	Technology	State of the Art	Requirements	Development Need
Root Zone Soil Moisture/ SSS/ Air-Sea Flux/ Sea Ice	Broadband/ Multiband Focal Plane Array Feed Technologies for Large (e.g. >7m) Antennas	Single band and/or multiple feedhorns	10-1 band feeds (options); non-moving conical scan; P/ L/ S/ C-band; 40° ONA; Multi-angle may also be useful	Combined Radar/ Radiometer/ SoOp; Multi-purpose SDR; reconfigurable frequency agile systems
High resolution imagery to support Snow/ OSWV/ Precipitation & cloud amount	6-/10-GHz through 90 GHz, spatial resolution substantially better than AMSR-2. (e.g., 6-meter deployable)	2m class apertures for multi-frequency space-based radiometers	~6-m reflector radiometer antenna; spatial resolution substantially better than AMSR-2. (e.g., 6-meter deployable); array receivers to accommodate Nyquist sampling	6m deployable reflector with surface figure to support W-band

Technology Needs: STAR Instrument Systems

Measurement(s)	Technology	State of the Art	Requirements	Development Need
Atmospheric Sounding;	Analog/Digital Cross Correlator	TRL 6	1-GHz IF band; 250 uW/correlation; 256x256 inputs; 500 MHz BW	*Still in review*
Root Zone Soil Moisture and Sea Ice	Distributed Correlators operating at P/ L/ S/ and C-band	TRL 3	<100 MHz; limited baselines in distributed STAR systems	*Still in review*

Technology Needs Trades

	P- /S-band 400-MHz to 2-GHz	C- /W-band 6- to 90-GHz	W- /G-band 100- to 200-GHz	SMMW 300-GHz to 1-THz
Measurement	Root Zone SM; SSS;	OSWV; SST; Imagery Ocean Altimetry; IWV Atmospheric Sounding; Cloud Amount; SWE	Atmospheric Temperature and water vapor profiles	Cloud characterization; cloud Ice
Antennas/ Aperture	up to 10m aperture vs. distributed correlation systems	Up to 7m aperture(s); multi-band FPA; cylindrical / offset parabola; STAR at GEO	Deployable 2m dia from 2.5U stowed volume – various altitudes	Deployable up to 1m – various altitudes
Radiometer	RFI mitigation – tunable notches, broadband radiometers; frequency agile	Low SWaP-C radiometers integrate-able with Radar systems	Low SWaP-C radiometers; Low power LOs; Direct detection; filter technology	Low SWaP-C radiometers; low power LOs; direct detection; LNA performance
Platform	3-D ranging; formation flying; UAV	Reliable 5-yr cube-sat bus; UAV; imaging on demand (hurricanes/ storms);	Reliable 5yr cube-sat bus; power limitations;	Reliable 5yr cube-sat bus; power limitations;
IT/ Data processing	Multi-sensor processor: Passive/Active/SoOp	Small sat data transmission;	Small sat data transmission;	Small sat data transmission;

Radiometer Technology Needs Summary

Band	P	L	C	X	K	K_a	V	W	G	smmW
Measurement	Soil Moisture		Ocean Wind Vector						Atmospheric Comp	
		Salinity		Snow Cover/Depth					Cloud Ice / Trop Proc	
				Precipitation				Precipitation		
					Cloud Liquid			Cld lqd		
							Temp		Humidity	
Antenna Feeds and Reflectors	Integrated active/passive multi-band front-ends / FPAs									
			Deployable 2m class							
	(10m) Large reflectors (7m)									
Receiver Electronics	Miniaturization (Integration: Active / FPA)						Miniaturization (SWaP-C)			
									LP LO	Performance
Calibration	Distributed Correlators		UAV				Direct SI-Traceability			
System	Distributed Correlators						Correlators		Correlators	
	Formation flying / STAR		EPBR Polarimetry							
			Constellation Management							

Preliminary Conclusions and Recommendations

- **Improvements in high frequency radiometer RF performance and SWaP-C**
  - Needed for several measurements including Cloud and atmospheric boundary layer, precipitation processes
  - Improved radiometer components desired (LNA's, filters, detectors, isolators) for operation at higher frequencies
  - Cryo-coolers may help, but may not be most effective path to the performance improvements desired
- **Multi-frequency and multi-sensor shared aperture measurements will drive developments in antennas and radiometer electronics**
  - Integrated Radar/Radiometer hardware allowing radiometer to coexist with radar systems
  - Multi-frequency FPA array designs to enable technology trades in Root Zone SM
  - Multi frequency feed for cylindrical antennas
- **RFI mitigation techniques in hardware and software**
  - Spectrum sharing techniques (notch filter, effective RFI detection and mitigation) is of increasing priority for low band measurements and especially needed for Radiometers attempting root zone soil moisture at P-band
- **Deployable apertures could enable measurement scenarios from smaller satellite platforms**
  - Current capability: 0.7m from 1.5U; this capability may continue to improve but best value goal is not clear
  - Larger class of stowed volumes commensurate with dual ESPA ring launch opportunities are also important
  - 6 – 10 m diameter apertures desired for improving spatial resolution of existing 'operational' measurements
- **Additional developments needed to support distributed/ multi-sensor approaches to lower cost**
  - Small platform reliability /power availability / data handling
  - Large constellation management/ modelling (additional discussion in emerging technologies)

- **State-of-the-Art and Future Requirements in Radar**
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C&DH Assessment for 2007 Decadal Survey Measurement Recommendations

Capability Gap	Measurements	TRL
Waveform generation/ultra-low-range-sidelobe pulse compression	Clouds (ACE - radar)	5
OSSE; mission configuration and performance studies	Aerosols, Clouds (ACE)	2-5
Information-aware compression algorithms for downlink and RFI mitigation	Atmospheric composition (GACM)	3
Advanced 3D tomographic retrieval algorithms	Atmospheric composition (GACM)	3
Retrieval algorithms	Snow water equivalent, depth, wetness (SCLP)	3

Other decadal missions (XOVWM, SWOT, PATH, NISAR/DESDynI) reported no unmet data processing technology needs

Enabling Technologies for New Concepts

Capability	Concept (measurements)	TRL	Challenge
Onboard storage	Synoptic, multi-sensor, and/or data-intensive measurements (e.g. land deformation, topography, vegetation height/density,…)	4-5	Capacity, speed, SWAP
Onboard processors	Rad Hard By Design, 3D ICs (applicable to wide variety of measurements; e.g., tasking for storm observation, range compression for profiling)	3-5	Performance, SWAP, reusability
Onboard algorithms	Adaptive beam forming, adaptive tasking, formation control, RFI detection and mitigation, compressive sensing, data reduction, data compression (applicable to wide variety of measurements)	2-4	Development, implementation
Fast ADCs	Wide-bandwidth radiometry – digitize 20+ GHz, adaptively channelize to mitigate RFI (RFI mitigation, atmospheric composition)	4	Power, performance for radiometry
High-speed, high-res digital correlators / spectrometers	RFI mitigation over up to 20+ GHz bands (applicable to wide variety of measurements)	4-5	Large BW, # of channels, SWAP

Enabling Technologies for New Concepts

Capability	Concept (measurements)	TRL	Challenge
Advanced radar waveform generation	Frequency and/or phase diversity for multiple, simultaneous independent looks (e.g. clouds, precipitation, storms)	5	Implementation, space qualification
Affordable continuous coverage/high revisit rates	Constellations of smallsats (e.g. temperature, moisture, precipitation, wind vector in dynamic environments)	3	Coordination, calibration
Automated event-driven operation, low-latency retasking	Hierarchical collection methodologies, dynamic reallocation of resources based on detected events/features (e.g. temperature, moisture, precipitation, wind vector in dynamic environments)	3	Robust event detection; rapid coordination
Inter-spacecraft metrology for ~cm-level formation control	Increased use of smallsats; synthesize larger apertures using formation flying (e.g. root zone soil moisture, sea surface salinity, air-sea flux measurements)	2-4	Low-SWAP-C metrology solution
Fast external data links	Data sharing among satellites in formation (e.g. root zone soil moisture, sea surface salinity, air-sea flux measurements)	3	Low-SWAP-C

Enabling Technologies for New Concepts

Capability	Concept (measurements)	TRL	Challenge
Fast, reliable downlink	Increased data production – multiple payloads, smallsat constellations, data-intensive SARs, … (e.g. precipitation, root zone soil moisture, cloud processes, deformation, topography)	3-5	Space and ground infrastructure, laser COMMs, SWAP-C/ specialization for smallsats
Ground data management	Big Data – petabyte storage, persistent teraflops processing, data fusion, distribution (applicable to wide variety of measurements)	3	Interoperability, tool development, efficiency, cost
Modeling, simulation, processing algorithm development	Enable new instrument/constellation concepts, new measurements/products, new CONOPS (applicable to wide variety of measurements)	2-3	Standards, interfaces, reusability

General Observations

- **Certain capability gaps are better categorized as engineering issues than technology**
  - *Adapting existing technologies*
  - *Instrument-specific retrieval algorithm development*

- **Technology investment should have clear payoffs**
  - *Enable new science, measurement capabilities*
  - *Improve quality, efficiency, or effectiveness of existing capabilities*

- **Several concept themes emerged during JPL/GSFC workshops**
  - *Adaptive processing and tasking*
  - *Coordination of multiple spacecraft*
  - *Handling of large data volumes*

- **Majority of technology development needs can be placed into the following overarching areas:**
  - *Onboard processing*
  - *Spacecraft control & communication*
  - *Ground processing*
  - *Algorithms/models*

Onboard Processing – Applications

- **Optimize data collection**
  - *Adaptive beam forming*
  - *Adaptive channelization*
  - *Efficient spectrum utilization*
  - *RFI detection and mitigation*
  - *Accommodations for instrument health*

- **Enable adaptive tasking**
  - *Data reduction for feature/event detection*
  - *Automated event-driven tip-offs; coordinated retasking of same or other spacecraft*

- **Enable formation flying**
  - *Process metrology inputs to inform station-keeping*

- **Aid downlink**
  - *Data processing and compression to reduce downlink requirements*
  - *Enable direct downlink to users*

Onboard Processing – Technology

- **Hardware development**
  - *State of the art:*
    - *Onboard storage: ~10 Tb, ~9 Gbps flash memory (NISAR Solid State Recorder)*
    - *Onboard processors: e.g. 50 MHz 32-bit ARM*
    - *ADCs/Correlators: 3 GHz*
  - *Technology development needed:*
    - *Rad-hard-by-design tools and 3D IC technology to improve performance and SWAP*
    - *Fast ADCs, ASIC polyphase spectrometers*
  - *Desired state:*
    - *Increased capacity & speed; decreased SWAP-C for storage and microprocessors*
    - *ADC w/ BW > 20 GHz, ENOB > 4, power < 2 W*
    - *Spectrometers w/ BW > 20 GHz (10 GHz I/Q), 1 MHz res*
    - *Spectrometers w/ BW ~ 2-3 GHz, 128 channels, < 2 W for low-freq RFI mitigation*

- **Algorithm/software development**
  - *Compressive sensing (e.g., sparse multi-sat apertures)*
  - *RFI detection and mitigation*
  - *Data compression*
  - *Efficient data processing (may be instrument-specific)*

Spacecraft Control and Communication

- **Smallsat constellations/formations**
  - *Replace big and expensive with small and cheap*
  - *System design requires modeling and simulation*
  - *Precise (~cm level) formation control requires low-SWAP-C inter-spacecraft metrology, communication, and processing systems development*

- **Adaptive tasking**
  - *Develop capability for systems to detect terrestrial events (e.g., storms) and autonomously alter collection strategies in response*
  - *Rapid, automated self-tipping and vehicle-to-vehicle coordinated retasking*
  - *Low-latency (~minutes) space-to-ground-to-space retasking*
  - *Requires onboard processing, inter-s/c links, CONOPS development*

- **Downlink**
  - *System must accommodate ever-increasing data volumes*
    - *NISAR alone ~ 3-4 Gbps*
    - *Other high-rate systems (LIST, ICESat-2, etc) may also approach ~Gbps levels*
  - *May require new infrastructure*
    - *Additional relays/ground stations*
    - *Optical links*

Ground Processing

- **Develop next-generation architecture to manage large amounts of data**
  - *Storage (NISAR alone will produce ~petabytes per year)*
  - *Processing (NISAR ~TeraFLOPs)*
  - *Dissemination – user interfaces, infrastructure*

- **Develop CONOPS to enable quick-turnaround, event-driven tasking**
  - *Real-time processing, automatic feature recognition*
  - *Responsive (~minutes) spacecraft commanding (automatic or human-in-the-loop)*
  - *Coordination of multiple sensors*

- **Develop standards, interfaces, and infrastructure to allow big data fusion, code/library sharing**
  - *Systems/protocols to store and/or access data from multiple sources (e.g., space-based instrument data, airborne data, buoy data, etc.)*
  - *Real-time model predictions on same time and spatial scales as data*

- **Flexible dissemination of scientific data and products**
  - *User interfaces to facilitate data mining, fusion*

Algorithms/Models

- **Modeling, simulation, and algorithm development**
  - *'Technology' vs. 'Engineering'*
  - *Instrument-specific, evolutionary retrieval algorithm development will be lower priority*
  - *Algorithms and models that are measurement-enabling or that transcend multiple measurement scenarios are more likely to merit investment*

- **Enabling or transcendent examples**
  - *RFI detection and mitigation techniques*
  - *Data compression algorithms*
  - *Software-defined/cognitive radiometry/radar*
  - *Compressive sensing (e.g. sparse cubesat apertures)*
  - *Formation modeling and simulation; onboard control algorithms*

Preliminary Conclusions and Recommendations

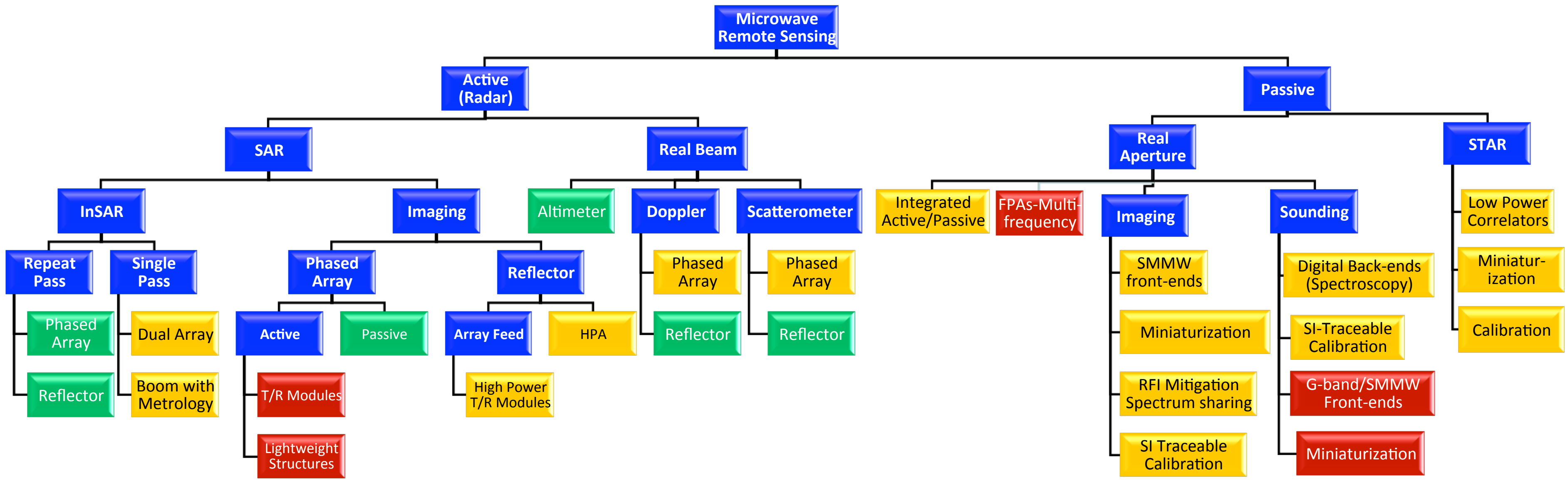
- **Emerging data-handling needs**
  - *Empirical, event-driven adaptive tasking and processing*
  - *Formation control*
  - *High data volumes/rates*

- **Investments required**
  - *Onboard processing hardware and algorithms, tasking CONOPS*
  - *Compressive sensing, formation modeling, inter-s/c metrology and communication*
  - *Data compression, down/crosslink infrastructure, ground data management*

- **Prioritize investments that enable measurements and/or transcend specific instruments**
  - *Onboard processing – RFI mitigation, data reduction and compression*
  - *Spacecraft control and communications – formation control, wideband downlinks*
  - *Ground – standards, interfaces, architectures, CONOPS, and infrastructure that enable big data storage and processing, sensor coordination, data fusion, sharing*
  - *Algorithms – modeling, simulation, and data processing*

- State-of-the-Art and Future Requirements in Radar
- State-of-the-Art and Future Requirements in Microwave Radiometry
- Data and Information Processing Future Requirements
- **Emerging Technologies and Trends**

Microwave Remote Sensing Taxonomy for Next Generation Measurements (Space)

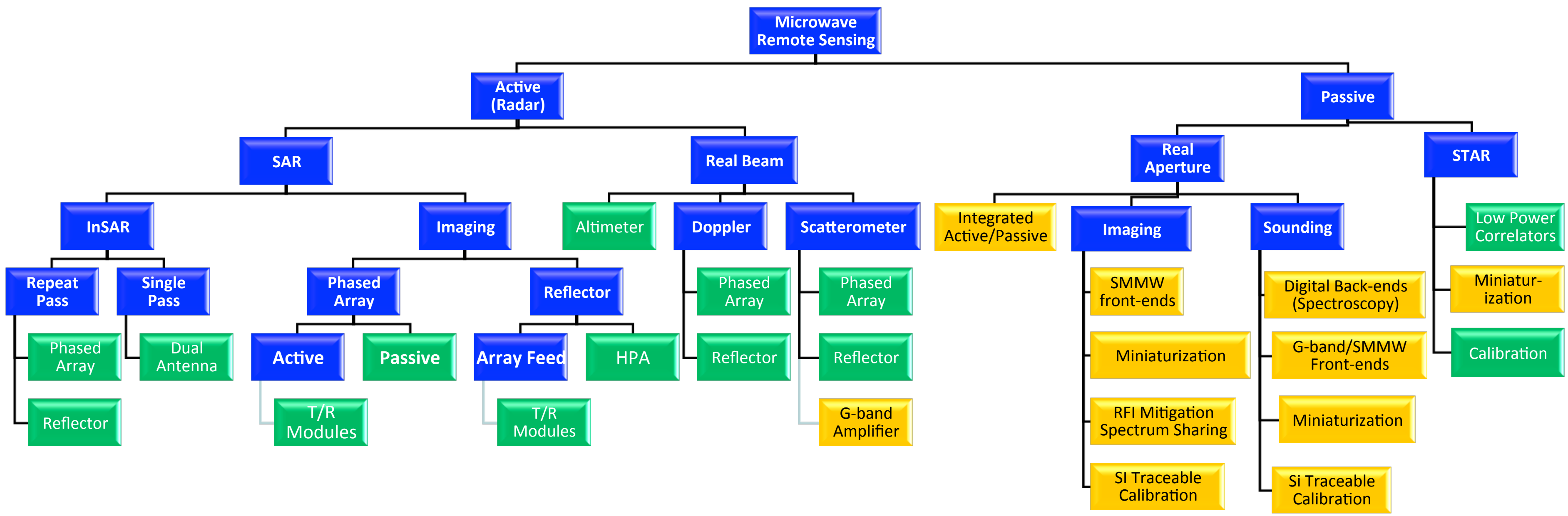


Key:

Space-Proven (TRL 7-9)
Developmental (TRL 4-6)
Experimental (TRL 1-3)

Each sensor/measurement has its own Command and Data Handling 'shadow', in addition to the cross-cutting IT challenges.

Microwave Remote Sensing Taxonomy for Next Generation Measurements (Airborne)



Key:

Flight-Proven (TRL 7-9)
Developmental (TRL 4-6)
Experimental (TRL 1-3)

Each sensor/measurement has its own Command and Data Handling 'shadow', in addition to the cross-cutting IT challenges.

Emerging Technology Definitions

- **Since the 2004 MWG report there has been a revolution in smallsat/hosted payload concepts, fueled in part by an increasingly (even aggressively) cost-constrained environment**
  - *In this paradigm miniaturization and low SWaP-C is key*
  - *Added low-cost launch opportunities create new measurement scenarios that were not envisioned in 2004*
  - *A new class/size range of deployable antennas is needed where overly restrictive stowed volume constraints are inconsistent with diffraction limited apertures of fixed size*
  - *May pursue ESPA-class launch volume sensors as a value added stowed volume constraint compared with cubesats*
- **The decision to actively address this emerging technologies in the 2016 report reflects a realization that new capabilities could greatly facilitate missions and measurement concepts**
  - *In this sense these new capabilities and the impact of increased access to space by universities and commercial interests cam impact approach to achieve new measurements*
- **For the current purpose we defined emerging technologies as being at a maturity level of <TRL3**
  - *TRL 2 is the entry point for ESTO's ACT and AIST programs*
- **System engineering as an emerging technology**
  - *Trades between aperture size, transmit power, altitude, integration of multiple sensor operating bands and/or active/passive sensors sharing a single aperture can greatly influence 'best value' in achieving a measurement*
  - *Requires robust, high-fidelity modeling and simulation capabilities that accurately represent the critical elements in science and engineering, of trade. This can be horizontal and vertical spatial resolution; radiometric resolution or sensitivity, temporal resolution or revisit time as well as SWaP-C.*
  - *Closely couple technology needs to measurement needs and flow requirements using model-based engineering and system engineering principles*

Emerging Technology for New Measurements

Capability Gap	Measurements	Current TRL
G-band technology at ultra low SWaP and transmitter technology for Radar	Humidity profiles	2
SMMW technology at ultra-low SWaP	Cloud Ice and Atmospheric Processes	2
RFI Mitigation improvements	Wideband spectrometer/ algorithms	2-3
Integrated Radar/Radiometer or multi-frequency Front-ends	Root Zone/Sea Surface Salinity/ Air Sea Flux	2-3
Very large antennas	Weather radar, hazard warning surface deformation, volcanic activity, ice	2
Inter-spacecraft metrology for formation control (aperture synthesis in formation flying)	Root zone soil moisture	2
High-speed, high-res correlators /spectrometers	Atmospheric composition; RFI mitigation	2-5
Constellation management for small satellites: platform reliability, data routing and management, system engineering tools	Root Zone Soil Moisture, Precipitation, Atmospheric Humidity	2

General Observations

- **TRL assessments depend on specific measurement attributes that did not appear to currently be firm**
  - Performance targets will dictate maturity and TRL
  - Some requirements were asserted for measurements (SWaP targets; correlator performance)

- **Multiple approaches to achieve new measurements in some cases**
  - High temporal revisits from LEO or GEO scanning approach
  - Integrated sensors with aperture sharing vs. separate sensor platforms
  - Adaptive tasking and coordination of multiple s/c vs. autonomous systems with continuous coverage

- **Multiple directions for some technology improvements**
  - *Direct detection vs. low power heterodyne configurations for G-band*
  - *Deployable 2-m class apertures from CubeSat or ESPA-class stowed volumes*
  - *Synthetic thinned aperture (correlators) vs real aperture (passive); Phased array vs. reflector apertures (Radar)*

- **Cross-cutting needs that would benefit multiple measurements**
  - High frequency (G-band and higher) improvements to SWaP-C and performance
  - Multi-frequency feed technologies to enable cost-effective multi-frequency/sensor measurements scenarios
  - Wide-band digital backend processing for RFI, spectrometry and polarimetry (passive), array feeds for reflectors

High Frequency RF Components and Systems

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
Front-end LNAs	Cloud Ice Atmospheric Composition Humidity	T_{sys}~350 K at 183-GHz; T_{sys}>800 K at 500 – 600 GHz	T_{sys}~300 K @ 500-GHz and 20 K ambient Power < 0.1W; Mass < 200g
Low Power Consumption LOs;	Cloud Ice Atmospheric Composition Humidity	GDOs or DROs + Multipliers >100mW DC power for ~10dBm RF output	MMIC-based superheterodyne integrated receivers: 300K at room temp @183 GHz Power <0.05W;mass<100g <1W; high level of integration; 5-10mW output up to 900 GHz
Ultra low power mmW front-ends	Water vapor and aerosol/cloud profiles	Combination of MMIC followed by CMOS receiver chipset has been demonstrated but only to 94 GHz; 300K at room temp @94 GHz Power <0.2W;mass<100g	300K noise temperature at room temp @183 GHz; Power <0.05W; mass<100g
G-band MMICs T/R modules; HPAs	Humidity; Cloud Ice	*Under review*	1-10W W-band T/R modules with integrated PA, LNA, phase shifter (4-bit), low loss T/R switches;. 1W PA and CW source; GaN

Multiple Frequency Integrated Elements (e.g. FPAs)

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
Broadband integration of radiometer and radar transmitter and receiver modules	Root Zone Soil Moisture Sea Surface Salinity Air-Sea Flux Sea Ice	Separate instruments or narrow band diplexer	Frequency range P/ L/ S-bands (400 MHz through 2-GHz) Low impact to the operation and performance of either sensor while reducing SWaP-C for multiple band measurements
Integration of Radar transmitter and receivers with radiometry	Precipitation	Frequency multiplexors and separate receiver chains	Instrument front-end with small SWaP; allows use of many units with fleet of cubesats
Integration of radar transmitter and receiver/ polarimeter	Ocean Altimetry Ocean Winds	Separate instruments	Single radar/ radiometer/ polarimeter to perform Ocean altimetry and/or scatterometry combined with polarimetry (passive)

Miniaturization of Sensors (SWaP; Deployables)

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
2-m class deployable antenna	Improved HSR for traditional measurements from small satellites; Precipitation Ocean Surface Winds Sea Ice Cloud liquid	6-m+ class deployable from larger rocket fairings; 0.7m deployable (TRL 6) from 1.5U; up to ~40 GHz for communication applications	Performance to ~600 GHz; stowed volume ~ 2.5U
MMIC-based radiometers and focal plane arrays covering multiple bands	Precipitation; Sea Ice; Cloud Liquid; Land Surface Characteristics	Discrete components and large feedhorn arrays driving SWaP for multi-band radiometer systems	Compact radiometer and reflector feed systems with deployable antennas reducing SWaP-C of traditional radiometer systems

Large Reflectors and Lightweight Materials

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
Very Large Antennas	Weather Radar, Surface Deformation, Volcanic Ash, Ice	10-m class reflector antennas (Communications pedigree)	Larger deployable antennas
Lightweight antenna structures	Weather Radar (persistent cloud /storm observation), Seismology, Hazard monitoring	Ground based, L-band, Doppler Weather radar	Space-based persistent observation

Sensor Calibration (Radiometers)

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
Direct SI-Traceable Calibration	In order of priority: Atmospheric Temperature Profile, Precipitation (multiple radiometers); water vapor, ocean surface and clouds	Individual radiometer cal/val and Cross calibration analysis with other radiometers	Uniform calibration between fleet sensors all traced to SI-standard
Improved Calibration of UAV-based Radiometers	Tasked observations of Precipitation/ Hurricanes or atmospheric temperature	Internal calibration targets and thermal sensors	Combine information about ambient environment to improve unattended airborne (vs. space-based) instrument calibration and achieve uniform calibration among several sensors and platforms
Distributed calibration for Synthetic Thinned Aperture Radiometers	Atmospheric Temperature, Water Vapor and Precipitation	*Under review*	*Under review*

Digital Processing Performance Improvements

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
High Speed Digital Backends	Atmospheric Composition; Polarimetry (OSWV; EPBR)	20-GHz Digital back-end	50-GHz
Broadband Radiometers	Imaging radiometry in areas of significant RF contamination	RFI detection and mitigation in BWs up to ~500 MHz	Spectrometer to support measurements anywhere from 1 – 50 GHz
Distributed Correlators	Root Zone Soil Moisture	Correlation of several small antennas within fixed frame	< 100 MHz BW with limited baselines in constellation

Next Generation Data Processing and Management

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
Ground data management	Weather prediction; L3 / L4 products from L2 products; Atmospheric boundary layer dynamics; global circulation	Mission centric data processing to L2 data and distribution to a few centers	Evolving data assimilation and fusion of L1/2 data to larger systems (e.g. NWP); ‘global’ distribution of vetted higher level products
Inter-spacecraft metrology for formation control	Root Zone Soil Moisture; Precipitation	Independent platform attitude control; limited dual satellite control (GRACE)	Inter-spacecraft metrology for formation control; control/ knowledge adequate to synthesize larger apertures using formation flying of small satellites
Fast external data links	Weather imagery; precipitation events	Data downlinks and ground based data exchange	Fast external data links; data sharing in formation to facilitate data processing/ attitude control; autonomous tasking

Emerging Technology Roll-up

	P- /S-band 400-MHz to 2-GHz	C- /W-band 6- to 90-GHz	W- /G-band 100- to 200-GHz	SMMW 300-GHz to 1-THz
Measurement	Root Zone SM; SSS;	OSWV; SST; Imagery Ocean Altimetry; IWV Atmospheric Sounding; Cloud Amount; SWE	Atmospheric Temperature and water vapor profiles	Cloud characterization; cloud Ice
Antenna/ Aperture	Up to 10m aperture vs. distributed correlation systems; Larger antennas for radar	Up to 7m aperture(s); multi-band FPA; cylindrical / offset parabola; STAR at GEO	Deployable 2m dia from 2.5U stowed volume – various altitudes	Deployable up to 1m – various altitudes
Radiometer	RFI mitigation – tunable notches, broadband radiometers; frequency agile	Low SWaP-C radiometers integrate-able with Radar systems	Low SWaP-C radiometers; Low power LOs; Direct detection; filter technology	Low SWaP-C radiometers; low power LOs; direct detection; LNA performance
Radar	T/R modules – extend down to P-band	C-/X-band Mature; W-band GaN T/R Modules	GaN T/R modules for higher efficiency; HPAs, very small SSPAs	N/A
Platform	3-D ranging; formation flying; UAV	Reliable 5yr cube-sat bus; UAV; imaging on demand (hurricanes/storms);	Reliable 5yr cube-sat bus; higher power;	Reliable 5yr cube-sat bus; higher power;
IT/ Data processing	Multi-sensor processor: Passive/Active/SoOp	Small sat data transmission;	Small sat data transmission;	Small sat data transmission;

Preliminary Conclusions and Recommendations

- **Multi-band integrated active/passive front-ends**
- **Multi-band phased array feeds for array–fed reflector based radars**
    - *High power, efficient GaN T/R modules*
- **Digital radar electronics**
    - *Waveform generators, beamforming, receivers*
    - *Apply cubesat technology to larger sats*
- **High frequency RF components and systems**
    - *Each constitutes a waypoint on the small-sat/U-class constellation roadmap*
- **Miniaturization of sensors to leverage low-cost and hosted launch opportunities**
    - *Cubesats – some measurements concepts drive very low TRL assessments*
    - *ESPA-class – may provide better value technology development targets depending on measurement parameters*
- **Higher digitization rates and data processing**
    - *Enables a wide range of capabilities RFI mitigation, spectrum sharing, spectrometers, polarimeters*
- **Radiometer Calibration**
    - *Different configurations of radiometers (shared aperture, STAR, UAV, formation flying, SI traceability)*
- **Next generation data management and communication**
    - *Microwave sensors require data handling from distributed systems without data volume constraints*